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AN ANALYSIS OF FOUR ERROR DETECTION AND
CORRECTION SCHEMES FOR
THE PROPOSED FEDERAL STANDARD 1024
(LAND MOBILE RADIO)

by

Carol A. Lohrmann

March 1990

Thesis Advisor

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Interoperability of commercial Land Mobile Radios (LMR) and the military's tactical LMR is highly desirable if the U.S. government is to respond effectively in a national emergency or in a joint military operation. This ability to talk securely and immediately across agency and military service boundaries is often overlooked. One way to ensure interoperability is to develop and promote federal communications standards (FS).

This thesis surveys one area of the proposed FS 1024 for LMRs; namely, the error detection and correction (EDAC) of the message indicator (MI) bits used for cryptographic synchronization. Several EDAC codes are examined (Hamming, Quadratic Residue, hard decision Golay and soft decision Golay), tested on three FORTRAN programmed channel simulations (INMARSAT, Gaussian and constant burst width), compared and analyzed (based on bit error rates and percent of error-free superframe runs) so that a 'best' code can be recommended. Out of the four codes under study, the *soft decision* Golay code (24,12) is evaluated to be the best. This finding is based on the code's ability to detect and correct errors as well as the relative ease of implementation of the algorithm.

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An Analysis of Four Error Detection and Correction Schemes for
the proposed Federal Standard 1024 (Land Mobile Radio)

by

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ABSTRACT

Interoperability of commercial Land Mobile Radios (LMR) and the military's tactical LMR is highly desirable if the U.S. government is to respond effectively in a national emergency or in a joint military operation. This ability to talk securely and immediately across agency and military service boundaries is often overlooked. One way to ensure interoperability is to develop and promote federal communications standards (FS).

This thesis surveys one area of the proposed FS 1024 for LMRs; namely, the error detection and correction (EDAC) of the message indicator (MI) bits used for cryptographic synchronization. Several EDAC codes are examined (Hamming, Quadratic Residue, hard decision Golay and soft decision Golay), tested on three FORTRAN programmed channel simulations (INMARSAT, Gaussian and constant burst width), compared and analyzed (based on bit error rates and percent of error-free superframe runs) so that a "best" code can be recommended. Out of the four codes under study, the *soft decision* Golay code (24.12) is evaluated to be the best. This finding is based on the code's ability to detect and correct errors as well as the relative ease of implementation of the algorithm.

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The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

APCO	Association of Public Safety Commission Officers
AWGN	Additive White Gaussian Noise
A/D	analog to digital modulation (usually infers D/A)
BER	bit error rate
C3	Command Control and Communications
CELP	Codebook Excited Linear Predictive Coding
COMSEC	Communications Security
dB	decibels (relative unit of measure, usually for noise)
DCA	Defense Communications Agency
DIRNSA	Director of NSA
DOJ	Department of Justice
DSP	Digital Signal Processing
EDAC	Error Detection and Correction
FM	Frequency Modulation
FS	Federal Standard
FSK	Frequency Shift Keying
FTSC	Federal Telecommunications Standards Council
IC	Integrated Circuit
ICASSP	International Conference on Acoustics, Speech and Signal Processing
ICEP	INMARSAT Codec Evaluation Proposal
INMARSAT	International Maritime Satellite
LMR	Land Mobile Radio
lsb	least significant bit
MI	Message Indicator
msb	most significant bit
NCS	National Communications System
NSA	National Security Agency

NSEP	National Security Emergency Plan
PDF	Probability Distribution Function
OOS	Out-of-Synchronization
QDPSK	Quadrature Differential Phase Shift Keying
QRC	Quadratic Residue Code
PN	Pseudorandom Noise
RF	Radio Frequency
S/N	Signal to Noise Ratio (usually measured in dB)

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I. INTRODUCTION

A. BACKGROUND

1. Why Land Mobile Radio Standards are Needed

Interoperability, connectivity and security of the U.S. land mobile radio (LMR) communications systems are important objectives at all levels - federal, state, and local. In many ways the U.S. falls short in meeting these communications objectives. "This situation is even more serious when viewed in the National Security Emergency Preparedness (NSEP) context" [Ref. 1]. During such an emergency, private users of a land mobile public safety system may need to communicate with federal defense and law enforcement agencies to effectively execute emergency operations. This is not currently possible.

Within the defense community, interoperability between various services is a longstanding problem. An example that illustrates the extent of this problem is provided by the communication problems encountered during the Grenada conflict. Many rumors have circulated about a soldier who used his AT&T card to call back to the continental United States by phone, since he could not communicate with soldiers on the other side of the island due to lack of radio interoperability.¹ For all future joint military conflicts, interoperability between the services is a necessity.

The absence of a federal communications standard for the LMR, until most recently, has encouraged the proliferation of a diverse group of technically incompatible LMRs. The fact that the commercial market has produced a wide variety of state-of-the-art equipment is good in one sense -- there is much to choose from and the competition in the commercial market place keeps the cost low. However, each manufacturer produces his own "best" product with no standards or guidelines to follow. Modulation schemes, for example, may be different. This makes communication possible only with someone who has pur-

¹ This story has never been substantiated.

chased a radio from the same vendor. But if the overall objective is to promote LMR interoperability across agency and service boundaries, then more thorough standardization is necessary.

2. Current and Proposed LMR Standards.

There is presently a LMR standard in place -- Federal Standard (FS) 1023. Because of its late adoption (September 1989), it did not have an impact on existing defense or civilian LMR systems; many incompatible LMRs were already fielded. FS 1023's near-term objective was to prevent further proliferation of incompatible systems until a new standard for future upgraded systems could be agreed upon.

FS 1023 will be obsolete in the near future, in part because "...increasing demands on the fixed spectrum availability along with overseas evolution towards narrower channels have caused the need for efficient spectrum use." [Ref. 2] Today, new technological advancements enable more efficient use of the frequency spectrum. FS 1023 is based on 25 kHz allocated channel spacing; the proposed standard, FS 1024, will require a narrower allocation of frequency channel spacing -- 12.5 or 6.25 kHz.

LMR interoperability, through the adoption of FS 1024, is an achievable mid-term goal. Such an LMR standard would help to alleviate both interoperability and spectral congestion concerns.

Because of the interest and justified need for a future federal standard, the National Communications System (NCS) office of Technology and Standards, the National Security Agency (NSA) and the Land Mobile Radio (LMR) sub-committee of the Federal Telecommunication Standards Committee (FTSC) are working together to develop Federal Standard 1024 to meet the future needs of all LMR users -- federal (civil and defense), state, and local. The official draft FS 1024 is expected to be released in Spring 1990 for 90 day industry coordination and comment [Ref. 3]. Other correspondents involved include the U.S. Department of Justice (DOJ), the Assistant Secretary of Defense for C3I, and the General Electric Company [Refs. 1, 4, 5, 6, 7, 8, and 9].

3. Advantages and Disadvantages of FS 1024

There are three clear advantages with the adoption of FS 1024. First, full and open competition between commercial LMR vendors will become healthier. Clearly the company with the best product for the money will win a competitive procurement. Second, a healthy market will produce a greater availability of LMR products. Third, it is likely that the standard will extend beyond the bounds of the intended commercial LMR market to the tactical defense radio market. This "status quo" effect, driven by the adoption of FS 1024, would have a positive influence on intra-service communications compatibility and interoperability.

Most often, each service provides the communications for its own units. There is a wide variety of tactical radios fielded for dozens of unique applications. It is more of an exception when these radios are able to interoperate. FS 1024 may be seen, then, as a first step in enhancing cross-service interoperability requirements for tactical (land mobile) units.

The main disadvantage of FS 1024 is that standardized radios would not be backwards compatible with existing radios that comply with FS 1023. An upgrading of all existing systems, a high-cost and highly unlikely proposition, would be necessary before full interoperability could be obtained. Over time this disadvantage will be lessened since an in-place Federal Standard for new LMR systems will ultimately drive the replacement of existing systems.

B. DESCRIPTION OF LAND MOBILE RADIO FS 1024

The narrowband digital LMR standard includes three criteria to ensure interoperability. These three criteria are:

- voice coding (digitization) technique,
- the radio frequency (RF) modulation technique,
- the cryptographic algorithm and cryptographic synchronization.

The voice coding technique refers to another federal standard - FS 1016.² This standard specifies CELP (codebook excited linear predictive) coding as the requirement. CELP coding will be implemented with a 8 KHz sampling rate. The algorithm itself contains three functions: short term spectral prediction, long delay adaptive codebook "pitch" searches, and innovative stochastic codebook search.

The second criterion, RF modulation, is still under consideration. Possibilities include 4-ary frequency shift keying (FSK), tamed frequency modulation (FM), quadrature differential phase shift keying (QDPSK) and $\pi/4$ shift QDPSK.³ Final selection will be based on spectral efficiency (minimizing adjacent channel interference) and power efficiency.

C. SCOPE AND GOAL OF THESIS STUDY

The third criterion, cryptographic algorithm and synchronization is the portion of FS 1024 on which this thesis will concentrate. The focus is on the error detection and correction (EDAC) scheme for the message indicator (MI) portion of the synchronization bits, within the allocated transmission format.

The goal of this study is to determine the most suitable EDAC code, among four -- Hamming, Quadratic Residue Code (QRC), Golay hard decision and Golay soft decision -- for cryptographically securable LMRs. Factors affecting the findings are also discussed. Analyses and findings are based on a computer simulation. The thesis only addresses block codes. Convolutional codes were eliminated from consideration by DIRNSA based on a study by NASA [Ref. 11]. Longer processing delays -- characteristic of convolutional codes -- are considered unacceptable for use in LMR, where a more immediate response is required.

² FS 1016 is proceeding through the FTSC approval process [Ref. 10: p. 3] and is expected to be approved by the Summer of 1990.

³ In an analysis performed by NSA, coherent and mainly noncoherent $\pi/4$ shift QDPSK were used. [Ref. 2]

D. ORGANIZATION OF THESIS

Chapter II discusses the transmission frame (bit) structure and proposed interleaving scheme. Interleaving and EDAC serve to mitigate noise induced errors.

Chapter III discusses and describes the EDAC codes considered.

Chapter IV describes the simulation and tests performed.

Chapter V presents the test results.

Chapter VI provides conclusions and recommendations for further study.

The appendix contains the FORTRAN code for the computer simulations used (Appendix A), the selected output data of the simulation runs (Appendix B), and the codeword interleave tables for each code type (Appendix C). Golay hard and soft decision use the same interleave table, therefore, there are only three algorithm 'types' out of the four codes tested.

E. THESIS COLLABORATION AND SUPPORT

This thesis was performed in consonance with DIRNSA R556 as an aid in their study and analysis of the FS 1024 issues for DIRNSA V2 (secure voice acquisition) and the National Communications System (NCS). Also, GTE Government Systems Corporation - Electronic Defense Communications Division in Waltham, Massachusetts is currently evaluating portions of the new FS 1024 for DIRNSA under contract number MSA904-90-C-6014.

II. TRANSMISSION FRAME STRUCTURE AND INTERLEAVING

A. FS 1024 SUPERFRAME AND FRAME

Figure 1 on page 7 shows the bit allocation for the FS 1024 data rate of 8000 bits/s. Table 1 on page 8 summarizes bit allocation and the respective bit rate for each superframe. For each second, 2400 are Error Detection and Correction (EDAC, or "parity") for the information bits, 4800 of the bits are information bits (CELP processed) and the remaining 800 bits are used for overhead processing. Bits allocated for overhead processing include bits for:

- framing
- mode control
- system control
- cryptographic synchronization (i.e., message indicator (MI) bits)

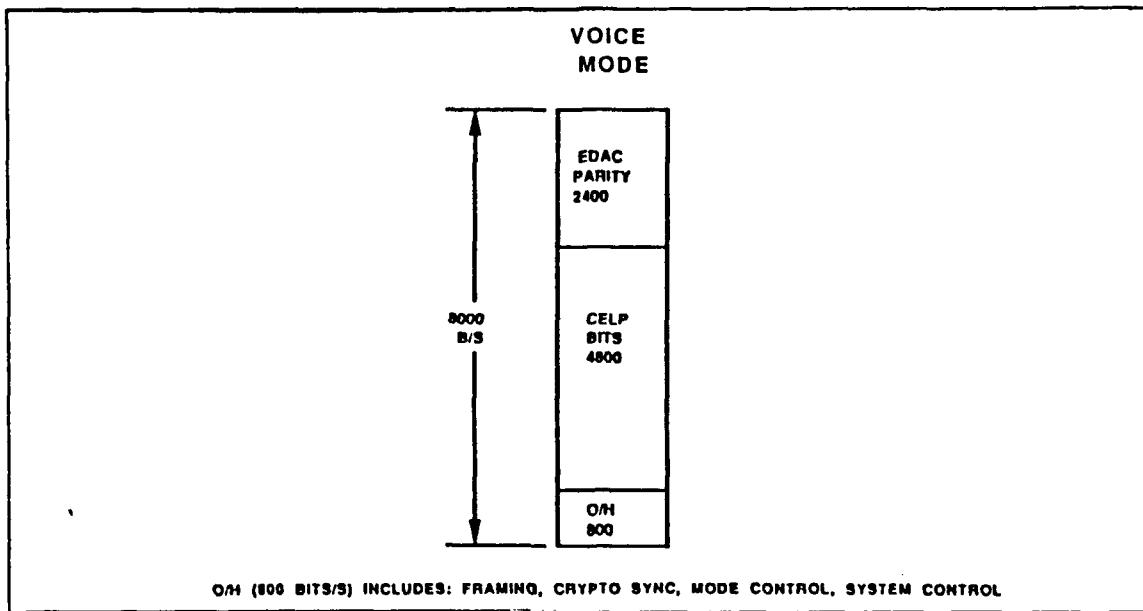


Figure 1. Data Rate Allocation (Source: GTE Government Systems Corp., LMR program review, Waltham, MA)

Table 1. SUPERFRAME BIT COUNT (420 MS)

	Bits SF	Bits s
Voice EDAC (parity)	1008	2400.00
Voice (CELP bits)	2016	4800.00
Framing	48	114.28
Mode Control (MC)	4	9.52
MC EDAC	10	23.80
Msg Indicator (MI)	72	171.42
MI EDAC	72	171.42
Reserved bits	6	14.29
System Control	124	295.24
Total	3360	8000

Adapted from GTE - Government Systems Corporation

For the recommended superframe transmission and interleaving format, there are 8 modes of operation defined by 4 bits in the 800-bit overhead control field: four are for the encrypted mode and four for the plain text mode. Only the encrypted voice mode, designated as 0100 in the mode control block, will be addressed in this thesis since the message indicator (MI) bits are not used in the unencrypted or plain text frame structure.

Figure 2 on page 9 shows the proposed frame structure for both the encrypted and the plain text mode. The shaded portion, the information superframes, is the only section of the message considered. The plain text mode does not incorporate EDAC or MI bits; thus, plain text superframes are half the duration.

Figure 3 on page 10 provides a one second snapshot of 8000 bits. Each superframe contains fourteen 30 msec frames. A total of 72 MI bits plus 72 MI parity bits will be interleaved throughout these 9 of these 14 frames, in a process

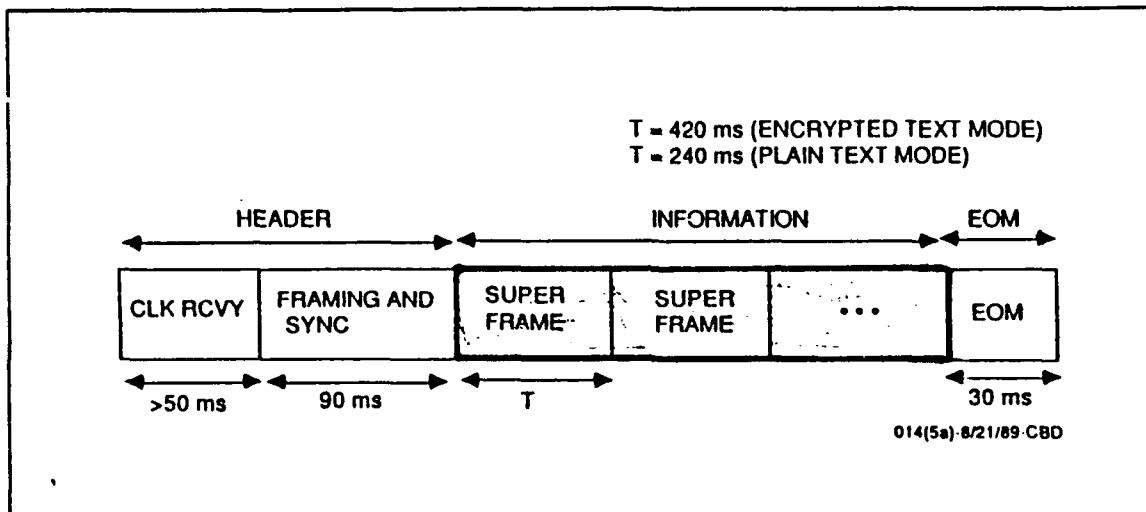


Figure 2. Transmission Format (Source: GTE Government Systems Corp., LMR program review, Waltham, MA)

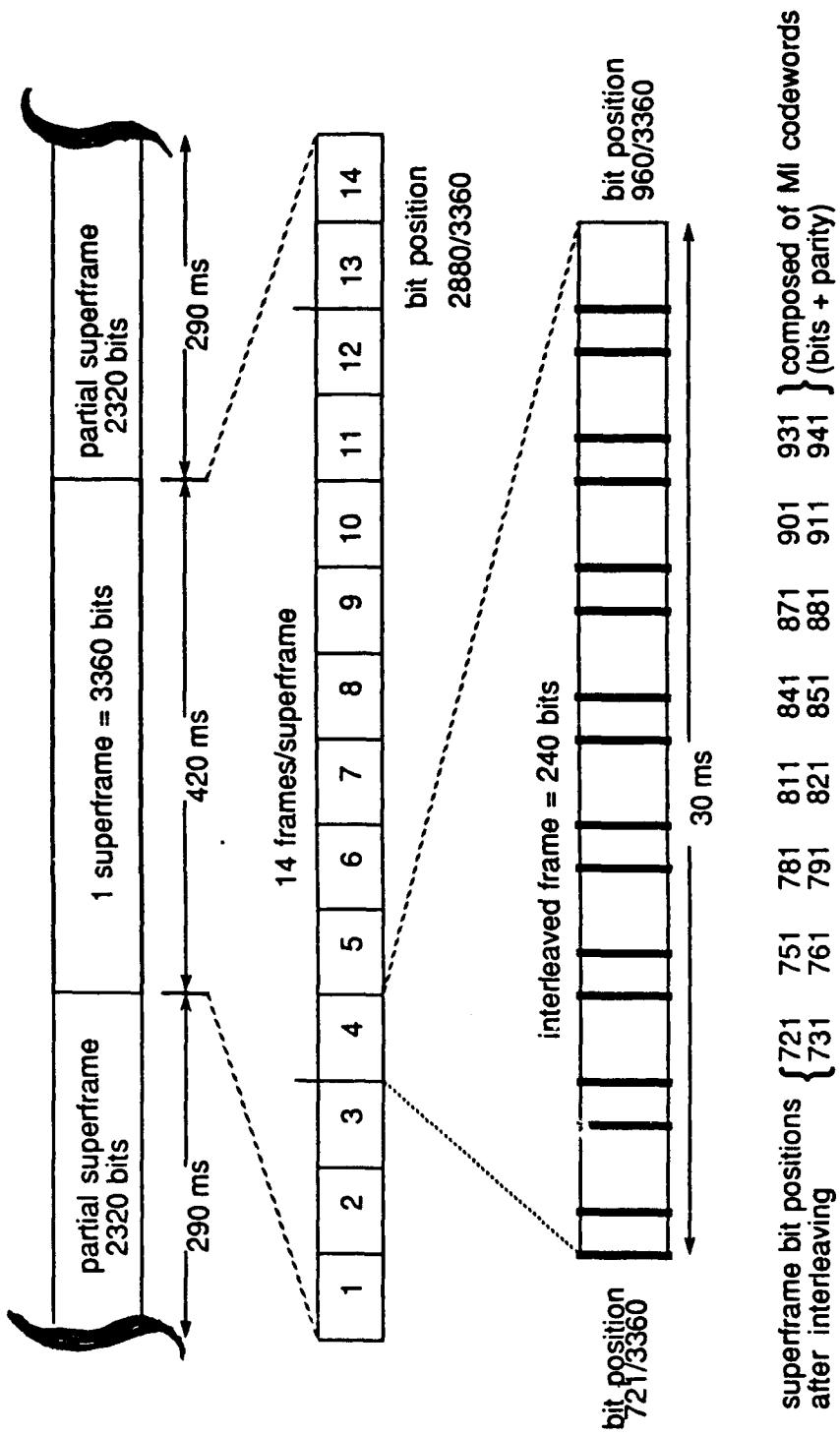
explained below. Three levels are depicted in Figure 3 on page 10. The top level depicts 8000 bits or $8000/3360 = 2.38$ superframes. The next level shows the superframe broken down into the fourteen 30 msec frames. Finally in the lowest level, one of these 240 bit frames shows the arrangement of the 16 interleaved bits within one frame. Of the 14 frames, frames 4 through 12 (only) contain the MI bits and MI EDAC (or "parity") bits.

B. PROPOSED INTERLEAVING

The process of *interleaving* involves dispersing critical bits over the superframe, in regular fashion, so that there is a smaller chance of these bits being corrupted by noise bursts. Interleaving ensures, for example, that the 72 MI bits and the 72 MI parity bits are spread in a pre-determined arrangement throughout the superframe. In this way a long noise burst will not corrupt these critical portions of the message. If the bits were grouped together, even a 10 ms burst (80 bits) could destroy the usefulness of the entire MI, and prevent successful cryptographic synchronization. Instead, by using an interleaving technique, only

One Second Snapshot (8000 bits)

Information Portion of Message



16 interleaved bits/frame \times 9 frames = 144 bits

a few of the critical MI bits may be corrupted; these should be detected and corrected by the interleaved MI parity bits.⁴

An evaluation was performed by GTE on two proposed interleaving schemes (I and II) for the FS 1024 superframe format [Ref. 12]. The testing was performed using mobile vehicles communicating in an urban environment. Scheme II outperformed Scheme I for vehicle speeds approximately three times slower in the five LMR frequency bands (132-172MHz, 406-420MHz, 450-512MHz, 806-512MHz and 851-866MHz).⁵ This is because the EDAC codewords (MI bits + parity bits) are more evenly interspersed over each frame in the Scheme II interleaver. The subsequent description and analysis address interleaver scheme II only, since FS 1024 will likely incorporate that scheme.

Figure 3 on page 10 also shows the interleaving scheme used by the EDAC computer simulation described in Chapter IV. Frames 1 through 3 are reserved for framing and mode control bits; Frames 13 and 14 contain system control bits. Every frame contains the voice - CELP processed information bits and its parity bits. The interleaving of MI bits and MI parity bits begins at the beginning of frame #4 or bit 721 and alternates skipping first 10 bits then 20 bits then 10 bits, etc. all the way through the frame #12 ending at bit 2680. Appendix C includes three codeword interleaving tables, one each for the Golay (24,12) code, the QRC (48,24) code and for the Hamming (8,4) code. The MI bits plus their parity bits (or "codewords") are broken up differently for the Golay, QRC, and Hamming codes to achieve maximum spread over frames 9 thru 12, the interleaving frames. For QRC the codewords are broken up into 4 bit chunks, for Golay the codewords are broken up into 2 bit chunks and for Hamming 1 bit chunks.

Figure 4 on page 13 illustrates frame composition for the QRC (48,24). For the QRC there are 3 codewords required (3×48 bits = 144 bits). Each codeword

⁴ More critical, however, is the interleaving of the MI parity bits. For if non-interleaved parity bits were corrupted by a noise burst, then MI bits also corrupted by another random noise burst would have no chance of being detected and corrected by the chosen EDAC scheme. At the very least, then, MI parity must be interleaved. Because of the random nature of noise however, both MI bits and their parity bits are both, optimally, interleaved.

⁵ For both schemes the lowest frequency band had the worst performance.

block pictured is a piece of one of the 3 codewords taken 4 bits at a time. All bits other than these 144 out of 3360 bits/superframe are treated as "don't care" within the analysis program. The EDAC protection of the information bits (CELP processed voice) was analyzed by NSA/R556 using Golay (hard and soft decision) code [Ref. 2].

In Chapter III, block codes and the codewords used for each code will be discussed in more detail. Most importantly, each code will be examined in terms of its ability to detect and correct errors.

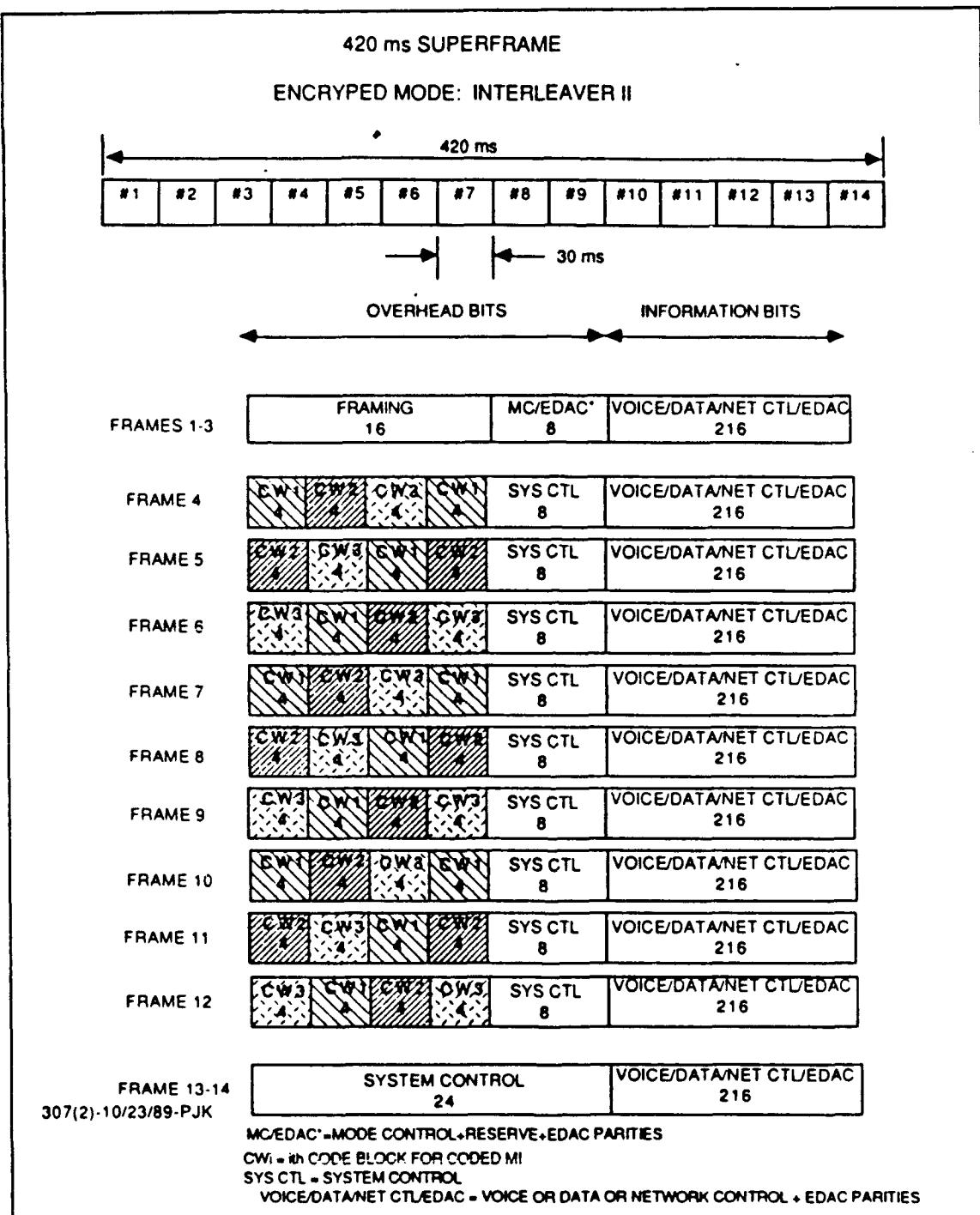


Figure 4. Superframe Composition (Source: GTE Government Systems Corp., LMR program review, Waltham, MA)

III. EDAC CODES EXAMINED

A. INTRODUCTION

All of the codes examined in this thesis -- Golay(24,12), QRC(48,24), and Hamming(8,4) are either in the class of (n,k) block repetition codes or (n,k) cyclic block codes. For n total bits/block and k information bits/block, the number of parity bits equals $(n-k)$, and code rate $R = k/n$. All of the codes have a code rate $R = 1/2$, which lends itself to easier bit manipulation.

For block codes, a generating polynomial, $g(x)$, is used to determine the parity checks performed. The number of parity bits determine the the number of checks performed. This parity check group is formed into a check matrix or **H matrix** for ease of manipulation.

The n -bit blocks (or "codewords"), formed by the product of the encoder (the parity bits) and information bits, becomes the transmit vector, $V(x)$. The received vector, before decoding, is designated $R(x)$.

Prior to decoding, a *syndrome* is used as a binary number block by the code algorithm to mark errors and the position of the errors for correction. If the syndrome equals zero, then there are no errors. The decoding and correction of the bits are algorithm dependent. Several different decoding schemes may be possible for each code.⁶

The number of possible errors corrected for a code is determined not only by the codeword size (n) and the information stream length (k), but by the minimum *Hamming distance*, d_{min} . This distance is the minimum number of bits that differ among all pairs of codewords in the code set [Ref. 16: p. 23]. The code can correct $1/2(d_{min})$ number of errors if d_{min} is even and $1/2(d_{min} - 1)$ errors if d_{min} is odd.

B. GOLAY CODES

The *perfect* cyclic Golay (23,12) code is a triple-error correcting code, and can be implemented in software. Typically, one extra bit is added to parity yielding

⁶ For derivations and more study on linear block codes refer to [Refs. 13, 14, and 15].

the Golay (24,12) code. This is done to maintain code rate = 1/2 and ease of algorithmic manipulation. The generating polynomial used is:

$$g(x) = x^{11} + x^9 + x^7 + x^6 + x^5 + x + 1$$

The Golay (24,12) code can be improved by utilizing analog information associated with the channel bits. In this way the bit error rate in white Gaussian noise can be improved about 2 dB. [Ref. 17] This "soft" decision-making uses the value of the previous baud to calculate confidence intervals. These confidence values are *real* values rather than actual baud values. This concept is illustrated by the constellation, Figure 5 on page 16 [Ref. 2].

The X and Y axes of Figure 5 on page 16 represent the least significant bit (lsb) and the most significant bit (msb) decision boundaries of the two baud being compared. The dot represents the unquantized phase difference between present baud and previous baud and the circle represents the magnitude at the present baud relative to the low-pass filter receive baud magnitude. The confidence for each sb is then the phase difference from the dot to its corresponding nearest boundary. Fades are flagged by scaling the amplitudes of the confidence values.

Sixteen iterations (2^4 bit patterns) are performed to search for and invert the bits designated by the Golay decoder as the lowest four confidence bits in the codeword. The errors are counted for each iteration and the bit pattern with the lowest cumulative confidence is selected as valid.⁷

For both Golay decisions, there are 6 codewords (24 bits codeword x 6 codewords superframe = 144 bits) generated for every superframe for the simulation.

C. HAMMING CODES

The Hamming (7,4) codes is a single error correcting code where all combinations of two errors are detected; only one error may be both detected and corrected. This code was the first error detection and correction code discovered, in

⁷ Bauds 10, 00, 01, and 11 correspond to phase changes 45, 135, -135, and -45 degrees, respectively.

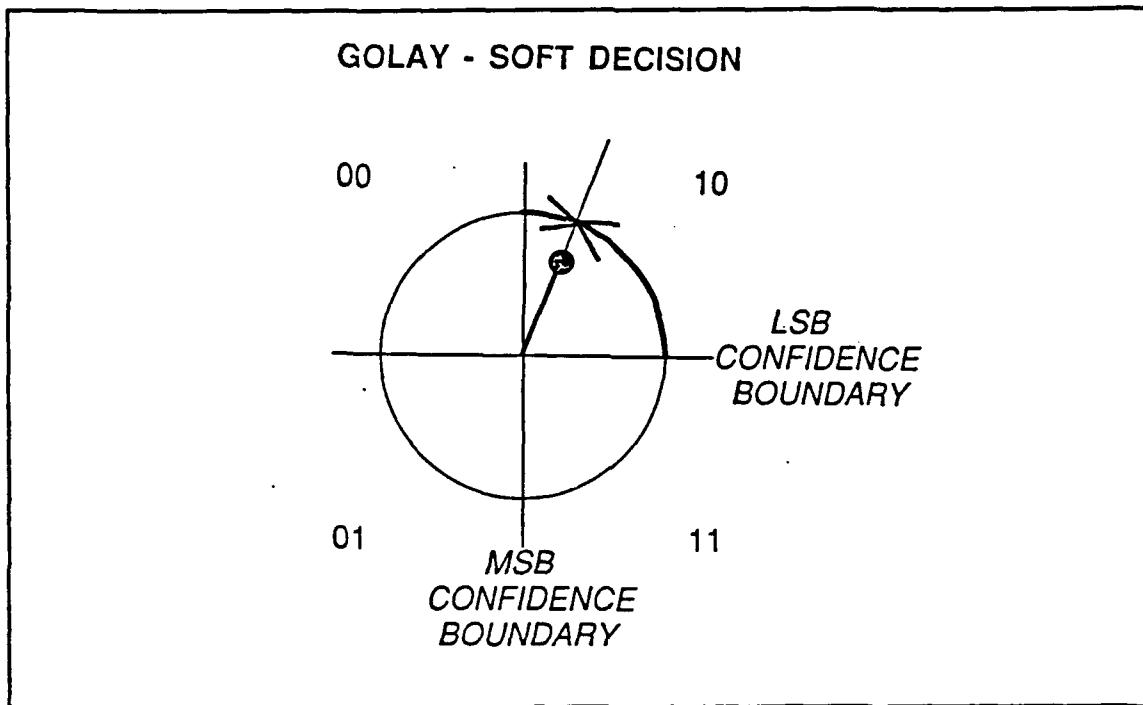


Figure 5. Confidence Constellation [Ref. 2]

1949 by R.W. Hamming [Ref. 18 : p. 13-29]. The modified (8,4) Hamming code is used for this analysis, where, 1 parity bit is added to maintain code rate $R = 1/2$.

For the simulation, there are 18 Hamming codewords (8 bits/codeword \times 18 codewords = 144 bits/superframe) generated for every superframe.

D. QUADRATIC RESIDUE CODE (QRC)

Quadratic residues are used to specify the roots of the code generator polynomial [Ref. 19: pp. 92,93]. They are defined by the numbers,

$$1^2, 2^2, 3^2, \dots, \left(\frac{p-1}{2}\right)^2$$

which are mod p reduced, where p is an odd prime number. Nonresidues are the numbers in the quadratic group that are not included by the residues. For ex-

ample, if $p = 19$, this would include all the mod 19 residues for $1^2, 2^2, 3^2, \dots, 9^2$. The following table, Table 2 on page 17, shows these values.

Table 2. QUADRATIC RESIDUES FOR
 $P = 19$

	residues	non-resid
$1^2 = 1$	1	2
$2^2 = 4$	4	3
$3^2 = 9$	9	6
$4^2 = 16$	16	8
$5^2 = 25$	6	10
$6^2 = 36$	17	12
$7^2 = 49$	11	13
$8^2 = 64$	7	14
$9^2 = 81$	5	15
		18

The QRC investigated by GTE is the (48,24) code, with $p = 47$. This code is capable of detecting and correcting 100% of 5 (or fewer) bit errors and 62% of 6-bit errors. The probability of correcting 6-bit errors is calculated with combinatorial logic as follows.

$$(47,24) + 1 \text{ parity bit} = (48,24)$$

The number of 5 or less correctable errors is:

$$C(47,5) + C(47,4) + C(47,3) + C(47,2) + C(47,1) = 1,729,647$$

Also, the codeword with one error must be accounted for, $C(47,0) = 1$. Since there are 2^{23} possible parity vector values (8,388,608),

$$8,388,608 - 1,729,647 - 1 = 6,658,900$$

is the number of possible parity combinations remaining to map into 6 or more error combinations. Next, the number of 6-bit errors possible within the 48 bit codeword is:

$$C(47,6) = 10,737,573.$$

Therefore,

$$6,658,960 \div 10,737,573 = .6202$$

This implies that the QRC will correct the sixth error in a 48 bit codeword 62.02% of the time.

There are 3 QRC codewords (48 bits/codeword x 3 codewords = 144 bits/superframe) generated for every superframe in the simulation.

The implementation of these EDAC schemes into a transmission simulation model will be discussed in Chapter IV. Also, the testing design approach and channel simulation models are introduced the next chapter.

IV. TESTS AND SIMULATION

A. DESCRIPTION OF THE PROGRAMS PROVIDED

1. Introduction

The program used in this analysis was provided by DIRNSA/R556, and was previously used by DIRNSA to evaluate the use of Golay (hard and soft decision) coding for the protection of the CELP information bits. A separate subroutine of the Hamming code was also provided, for integration into the main program. Program subroutines neatly divided most of the program chores (i.e. bit generation, encoding, modulation, decoding, bit error count, etc.).

2. Modifications

The program code was loaded and run on a VAX 11/785 mainframe in the ECE Department at the Naval Postgraduate School after conversion from Sun III FORTRAN to Berkley FORTRAN 77. The program was further modified to incorporate the Hamming code simulation and a bit error counter for the QRC. The encode/decode functions of the QRC are not included in the simulation - only a counter based on the code's probability of error detection and correction within a codeword.⁸

B. SIMULATION DESCRIPTION

Figure 6 outlines the simulation process in block fashion. The process begins as a pseudorandom (PN) bit stream, representing the MI bits, is produced for each superframe. Next, the 72 MI bits are encoded by the chosen EDAC, with "no code" representing the default control. The encoder generates the 72 parity bits to formulate a completed codeword of 144 bits.

The 144 bits are then hashed. This hashing process is in reality a pre-interleaving step that enhances the spread of the codeword bits throughout the

⁸ At this writing GTE is looking at simulating the QRC. However, the algorithmic implementation is much more complicated than even the Golay codes. Therefore, actual QRC encoding and decoding is not attempted in this analysis.

superframe.⁹ For each codeword the first bit is stacked, next the second, the third and so on. These realigned bits are then interleaved in Scheme II fashion, as described in Chapter II. To fill the rest of the 3360 bit superframe, an arbitrary PN bit stream is produced. The codeword bits are interleaved among these fill bits.

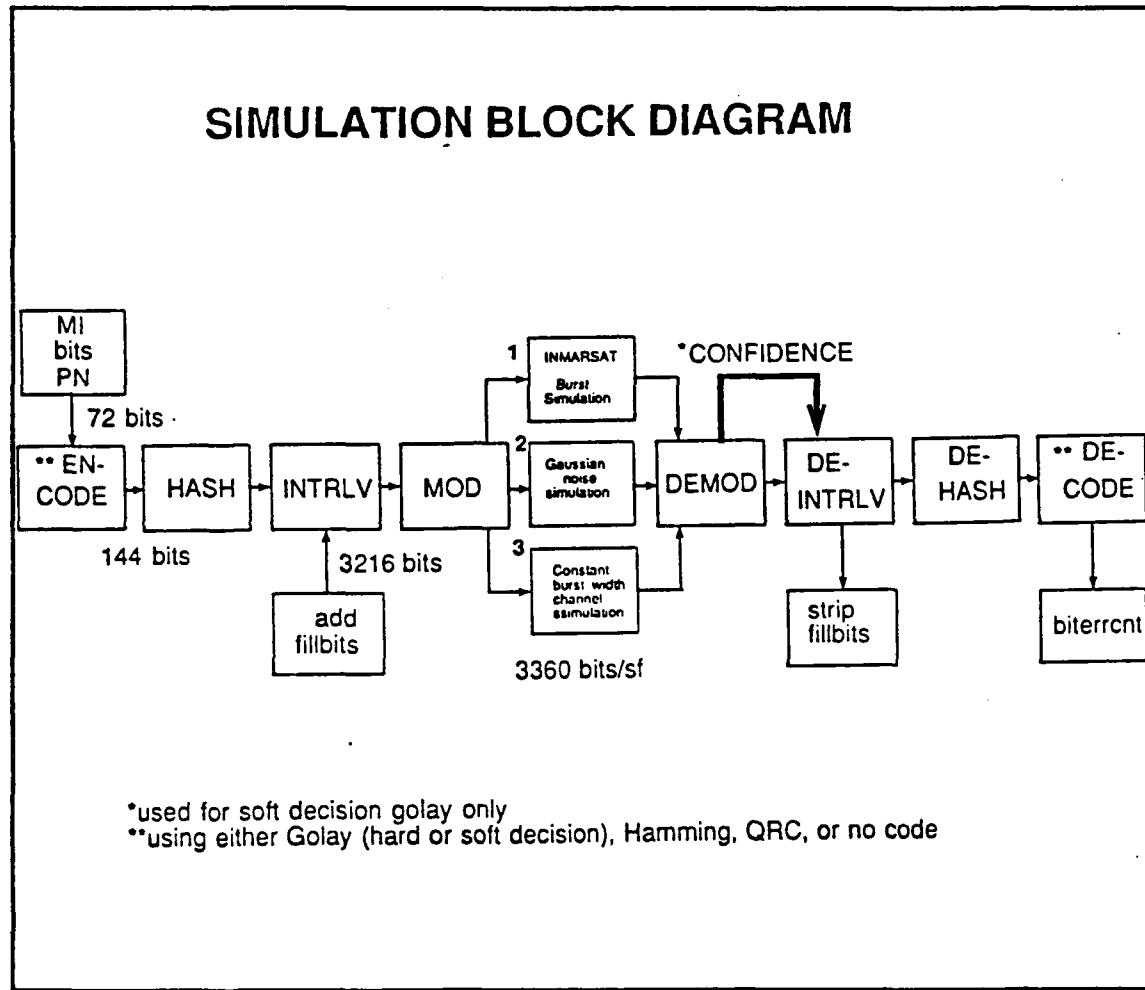


Figure 6. Simulation Block Diagram

Before modulation and transmission, the bits are changed to baud using a dabit representation as shown in Table 3 on page 21. The entire superframe is modulated and transmitted, then sent over one of three user-chosen simulation

⁹ This process is not reflected in the codeword interleaving table in Appendix C.

channels. The transmitted bits, now with simulated errors, are received and demodulated, deinterleaved, stripped of the 3216 non-applicable bits, de-hashed, decoded and checked for errors.

Table 3. BIT/BAUD EQUIVALENT

dibit	baud
0 0	0
0 1	1
1 0	2
1 1	3

Figure 7 illustrates the simulation design approach. Each section of the matrix represents one simulation run, for a total of 80 runs (5 codes x (1 INMARSAT CH + 8 AWGN CH + 7 constant burst CH)). A simulation run consists of 200 consecutive superframes. In all cases, the first superframe was expended for synchronization purposes. Thus, there are 199×420 ms or 83.58 seconds of established continuous information flow, which is likely much greater than an average message transmission. During the 83.58 second period, continuity of the digital signal is maintained unless bit synchronization is lost due to fade or noise.

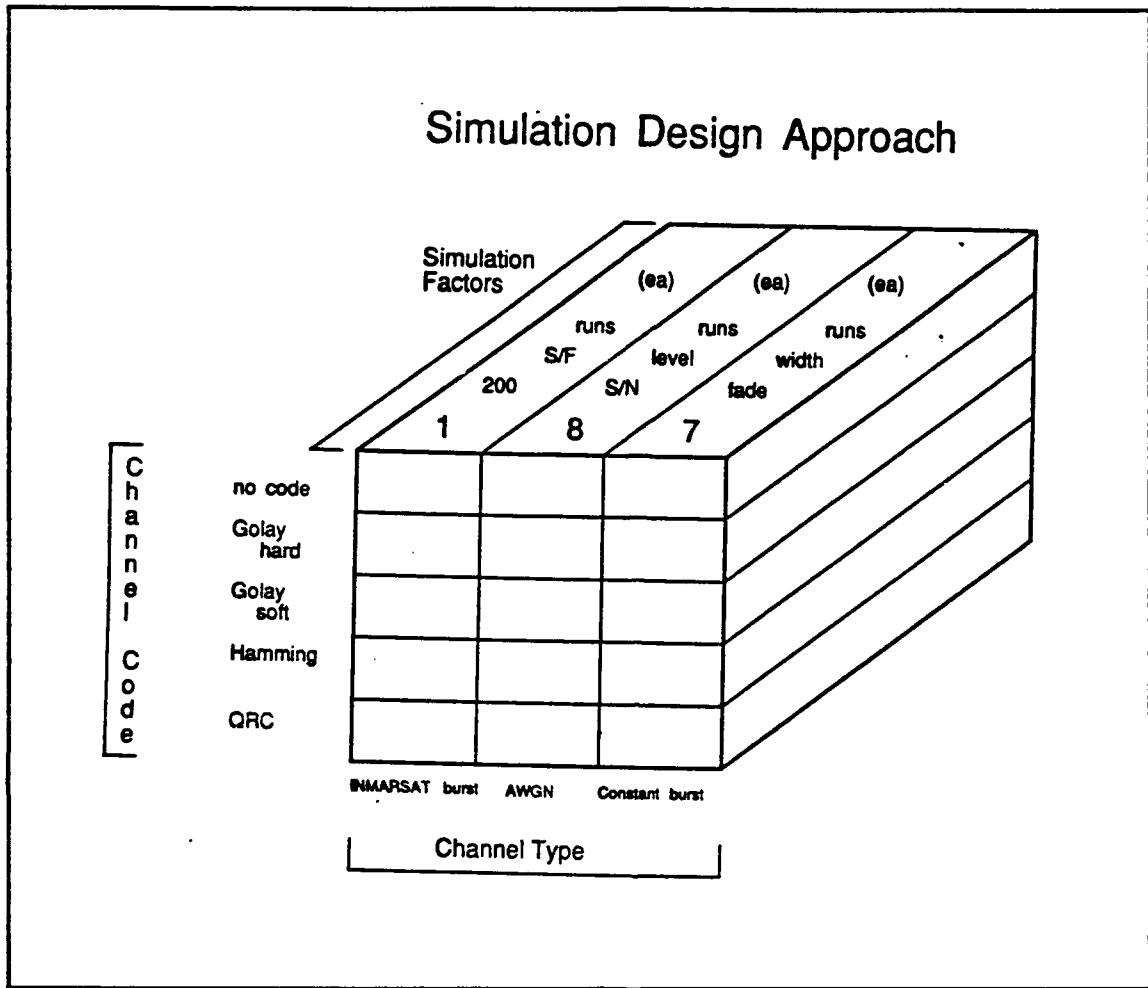


Figure 7. Simulation Design Approach

All simulation runs record the number of errors (within the 144 EDAC bits/superframe - location of an error is unknown) out of the total number of EDAC bits processed. Also, the number of successful and failed (S/F) superframes are recorded. Even one uncorrected error results in a superframe failure.

C. CHANNEL SIMULATIONS

The "mode" and "vary" variables provided for each channel are simulation selectable variables which determine the channel simulation mode.

For the simulation model, during *fading* or burst mode sequence the signal was subjected to -24 dB S/N and the signal strength divided by 200. This was

injected to ensure a 50% Bit Error Rate (BER) during burst error as required by the INMARSAT model. During non-burst error intervals, the S/N could be at any level. This parameter is user specified. For the two burst channel simulations, the S/N was set equal to 99.0 dB to ensure a clean signal. Therefore, *all of the errors* are a result of the signal fade. In the Gaussian channel the S/N parameter was varied from 0 to 7 dB. For the Gaussian channel, simulation errors were a result of poor S/N levels only.

1. INMARSAT Burst (mode = 1, vary = 0)

For the random burst noise (signal fade) channel simulation, the "simplified Land Mobile Radio channel model for IMARSAT Codes Evaluation Proposal (ICEP)" was used [Ref. 20: pp. 9,10]. The model is described as follows:

"The model is derived from realistic empirical propagation measurements such that performance of voice codecs can be tested in the laboratory with replicable situations. 90% is chosen as the link availability figure in the simplified model. The model is basically an ON-OFF model in which fading is in a binary state. The ON-state should correspond to no transmission whereas the OFF-state corresponds to 50% BER."

The discrete probability density function (PDF) for the permissible noise burst widths are shown in Table 4 on page 24. The distribution of the burst widths for the INMARSAT channel is base on a random process. Therefore, the number of bursts for each burst width varied. For all but 200 msec burst widths, the actual number of bursts for each burst width were not significantly different from that predicted by the PDF.

Table 4. SIMPLIFIED FADE DURATION PDF

Fade (ms)	Prob
10ms	0.8
20ms	0.1
40ms	0.05
100ms	0.04
200ms	0.01

For the burst-noise channel simulation, one 200 superframe run was performed for each of the four codes and one run with no coding. An example of 3-second Golay-encoded signals, transmitted over an INMARSAT burst-noise channel, is shown in Figure 8 on page 25.

2. AWGN Channel (mode = 0, vary = 0)

For the additive white Gaussian noise (AWGN) channel simulation, signal-to-noise ratio (S/N) was varied from 0 to 7.0 decibels (dB) in 1.0 dB increments. Thus forty simulation runs (5 code modes x 8 S/N levels) were performed.

3. Constant Burst Width (mode = 1, vary = 1)

For the constant burst width channel simulation, a constant fade depth (or burst width) was inserted at random time intervals. Seven discrete fade widths -- 5, 10, 20, 40, 100, 200, and 400 milliseconds -- were run for each code. Thus, thirty-five simulation runs (5 codes x 7 burst widths) were performed, each having 200 superframes. The 5 and the 400 msec burst widths, not included in the INMARSAT model, were added to observe the limits of the model and the performance of the codes.

INMARSAT CHANNEL PERFORMANCE

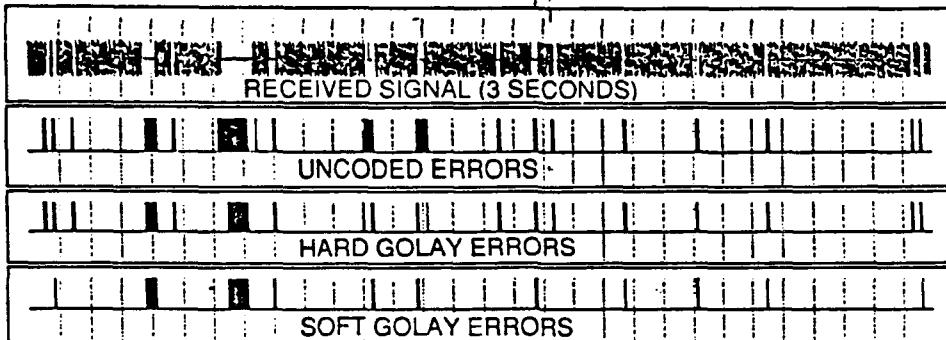


Figure 8. INMARSAT Channel Performance [Ref. 2]

Figure 9 shows constant amplitude signals subjected to varying fade widths. One second translates to 2.38 superframes.

Using the same outline as Chapter IV, the test *results* are presented in Chapter V by channel simulation type. The BER results and S/F results for each simulated code over each of the three channels is displayed and compared.

VARYING FADE WIDTH SIGNALS (1 SEC)

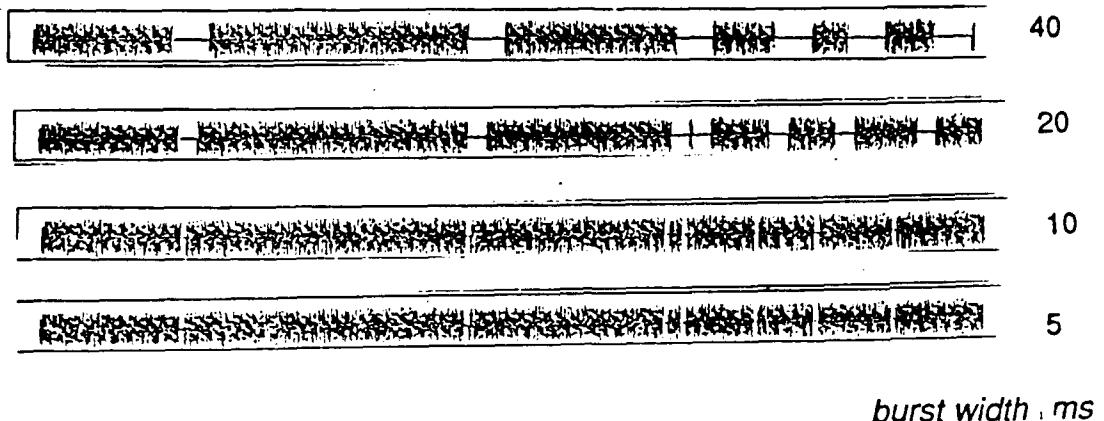


Figure 9. Varying Fade Width Signals [Ref. 2]

V. COMPARISON AND ANALYSIS OF TESTS

For each of the three simulated noise channels, the codes are rated in terms of BER performance and in terms of number or percentage of successful (or "error-free") superframe transmissions. BER results are expressed as the BER exponent.¹⁰ This number is calculated by taking the \log_{10} of the number of errors counted divided by the number of bits transmitted.

The code abbreviations used in data tables are:

- **g(s)** - soft decision Golay (24,12)
- **g(h)** - hard decision Golay (24,12)
- **none** - no channel coding
- **ham** - Hamming (8,4)
- **QRC** - quadratic residue code (48,24)

A. INMARSAT BURST CHANNEL

1. BER Results

Table 5 on page 27, reflects BER results as the log of the quotient (number of errors counted divided by the number of bits transmitted). All BERs are greater than $10^{-1.2}$ for this simulation, which implies greater than 1 error out of 100 bits. These performance values are intuitively reasonable for LMR operations in an urban environment.

Table 5. A FUNCTION OF INMARSAT BURST NOISE, ALL CODES

	g(s)	g(h)	none	ham	QRC
BER exp	-1.5003	-1.4342	-1.3363	-1.5243	-1.8153

Also, the difference between the hard and soft Golay is only about 0.5%, while the QRC outperforms the soft Golay by more than 1.6%. This may be a reflection of the number of "long" bursts. For the pseudo-random process, the

¹⁰ The convention in [Ref. 2] was followed.

$g(s)$ suffered eight 200 msec fades while the QRC was only forced to process 2. If these additional bursts happened to span the critical MI bits in the $g(s)$ codewords, the BER would have increased.¹¹ Looking at the INMARSAT PDF, Table 4 page 24, the 200 msec bursts only have a 1% probability of occurrence. The difference between the number of 200 msec fades for the $g(s)$ and the QRC runs is therefore, insignificant.

Figure 10 on page 29, derived from table 5, shows the BER performance advantage that the QRC has over the other codes for this simulation. The QRC detected and corrected 1.5% more errors than the $g(s)$.

2. Run Success/Failure Results

Table 6 on page 28 reports the number of successful runs in the simulated INMARSAT channel, for each code.¹² While BER performance favors the QRC in an INMARSAT noise channel, the QRC only ran an additional two successful superframes out of 199. That is less than a 1% performance difference. Nevertheless, the QRC and $g(s)$ are noticeably superior than the other codes and the uncoded channel.

Table 6. INMARSAT BURST - #SUCCESSES/#FAILURES

	$g(s)$	$g(h)$	none	ham	QRC
#successes	171	162	81	134	173
#failures	28	37	118	65	25
#total runs	199	199	199	199	198
%successful	86	81	41	67	87

¹¹ This simulation did not allow the control of the number of bursts of each width. Therefore, it was impossible to inject the codes with the same error occurrences.

¹² If the number of successes and the number of failures do not add up to 199, the runs not accounted for are out-of-synchronization (OOS) superframes. If there are too many errors the transmission falls OOS and retries until a success or a failure is achieved. In any of the channel simulations the OOS runs are not counted toward the total number runs.

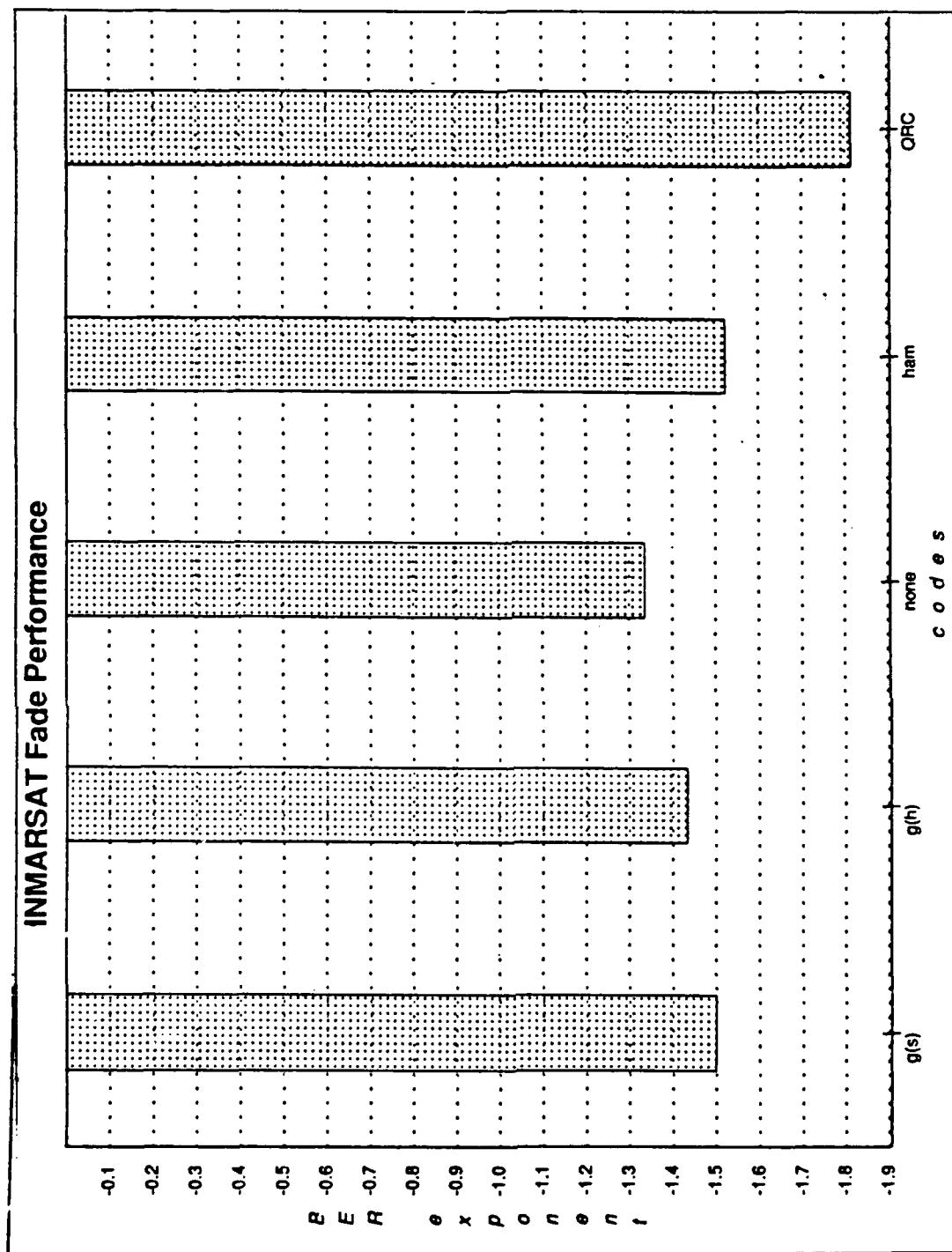


Figure 10. INMARSAT BER Performance

3. Additional Tests

Further testing was performed to check the validity of the INMARSAT simulation results. An additional 1000 superframes were run for both the $g(s)$ and the QRC. Again, the QRC outperformed the $g(s)$ in BER by .62%. The QRC also provided 2% more successful superframe runs than the QRC.

There seems to be a trend, in that the performance difference between the two codes appears to narrow with more superframe runs. This hypothesis could be tested with even more superframe runs. Nevertheless, the BER difference of less than 1% leads to the conclusion that there is no significant difference between the INMARSAT channel performance of the two codes -- $g(s)$ and QRC.

B. GAUSSIAN NOISE CHANNEL

1. BER Results

Table 7 on page 31, tabulates BER exponent for the 40, 200 superframe runs performed in the simulated Gaussian noise channel.¹³ Figure 11 on page 32 is derived from Table 7, and shows that $g(s)$ outperforms QRC at S/N levels greater than 5 dB. The figure also shows that the $g(h)$ outperforms the QRC at S/N levels greater than 6 dB. At S/N levels less than or equal to 5 dB, the $g(s)$ offers a slight improvement over that of the QRC and the $g(h)$.¹⁴

¹³ No errors were counted at 7 dB for $g(s)$ out of codeword bits; the BER exponent of -4.0 was used as a graph limit.

¹⁴ For the Hamming code, extra data points were taken; they are reflected in the graph only and not the table.

Table 7. BER AS A FUNCTION OF GAUSSIAN NOISE LEVEL, ALL CODES

	g(s)	g(h)	none	ham	QRC
0	-0.6055	-0.5638	-0.6421	-0.6108	-0.654
1	-0.7447	-0.6615	-0.719	-0.7072	-0.7525
2	-0.9547	-0.8125	-0.8153	-0.829	-0.9014
3	-1.2388	-1.0526	-0.9281	-1.0036	-1.1537
4	-1.6126	-1.3487	-1.0605	-1.2069	-1.556
5	-2.2676	-1.8297	-1.2269	-1.4724	-2.1586
6	-3.2343	-2.8761	-1.4056	-1.7447	-2.6198
7	-4.0	-3.1549	-1.6234	-2.1707	-2.8339

Figure 12 on page 33 is another representation of the same data. Code performance is compared at each S/N level measured. For each code, as the S/N increases the BER decreases. There are no surprising trends for any code. These two factors -- S/N and BER -- are inversely proportional and the comparison chart best illustrates this response. Also, the difference between the codes response at various S/N levels is more easily observed on this comparison chart than on the previous line graph.

2. Run Success/Failure Results

Table 8 on page 34 displays the number and the percent of successful runs with the OOS runs excluded from the total. These calculations were made using the total number of successful runs over the total number of runs performed. The g(s) code outperforms other codes in the gaussian environment, especially at lower S/N, which are more realistic in an LMR environment.

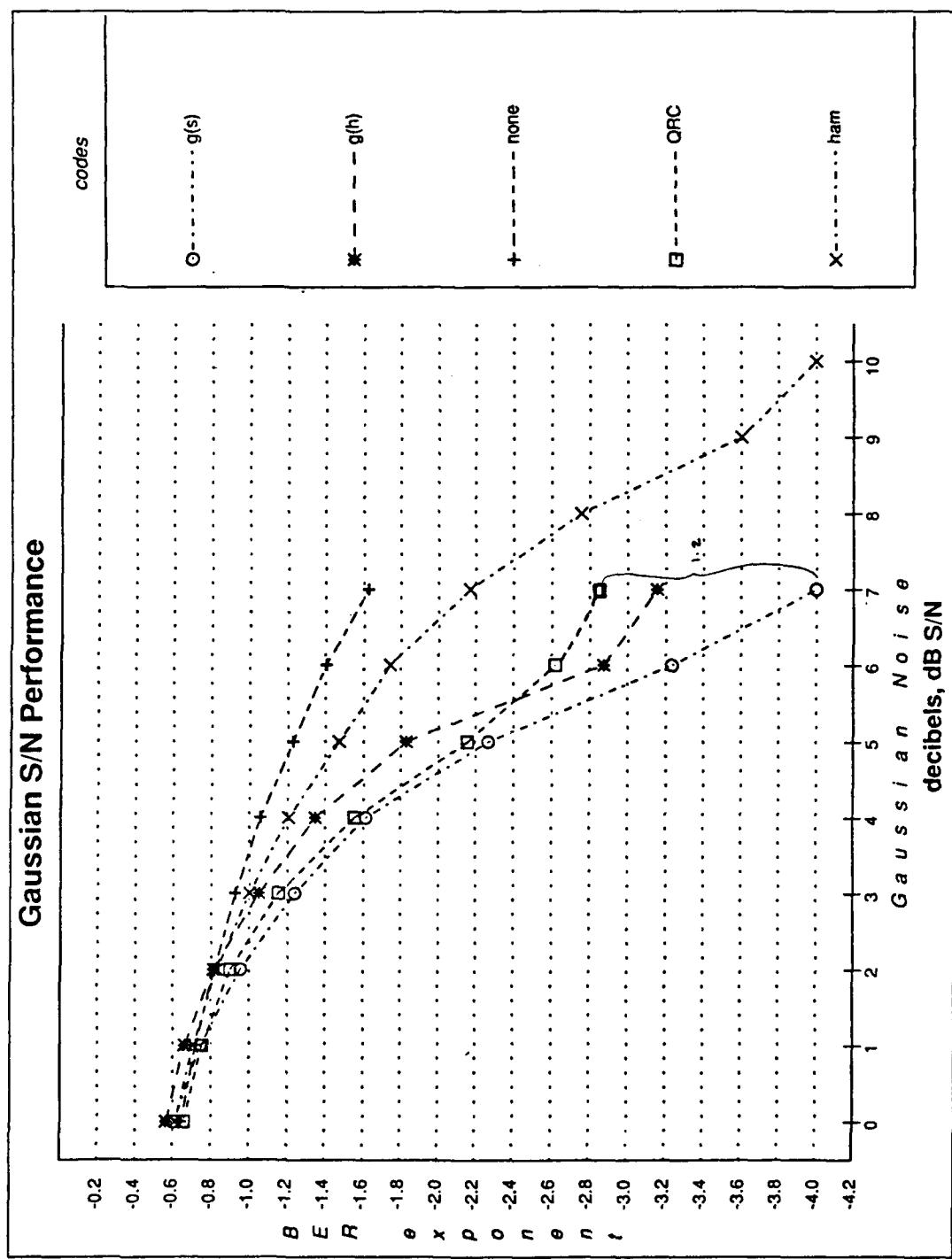


Figure 11. Gaussian BER Performance (line graph)

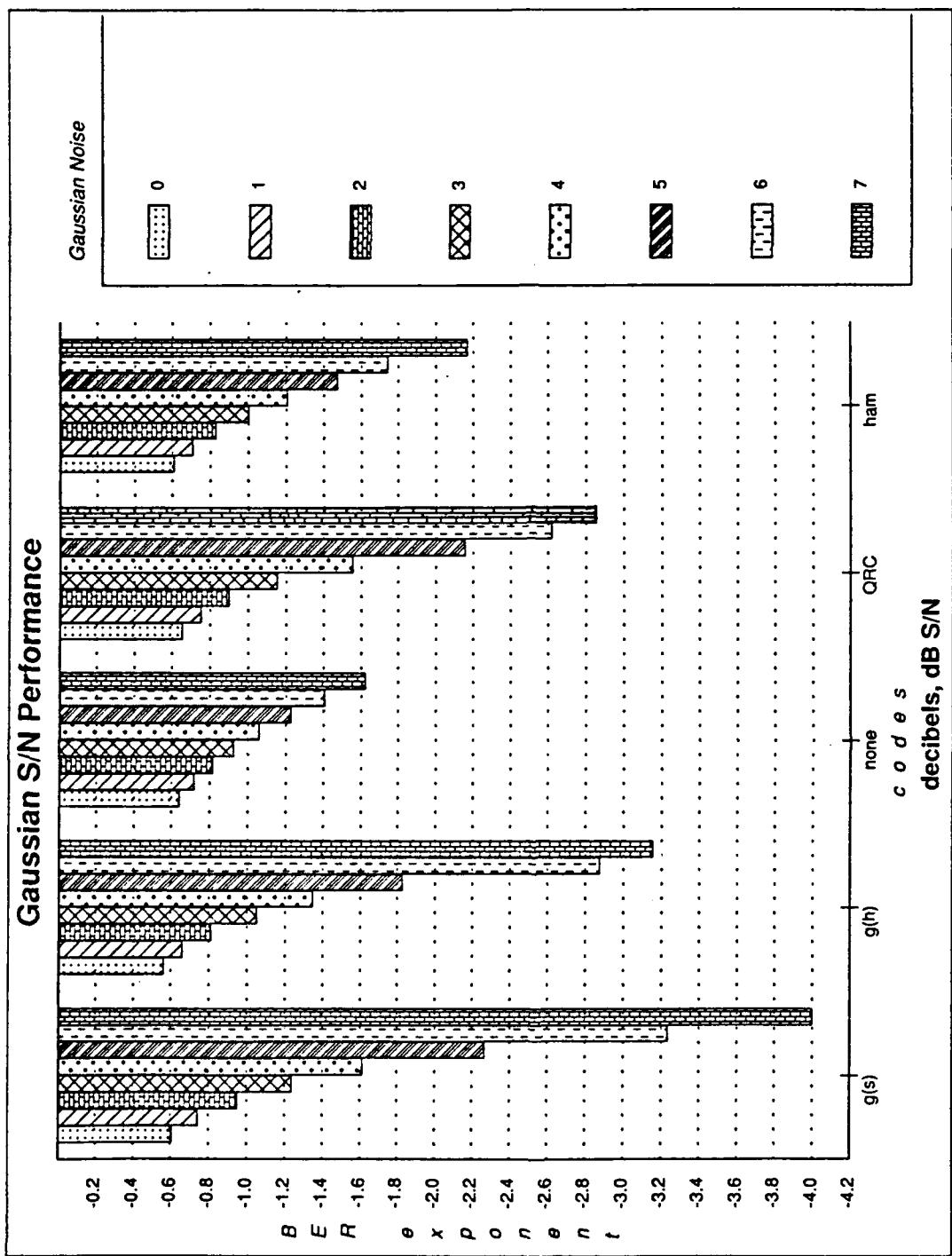


Figure 12. Gaussian BER Performance (bar chart)

Table 8. #SUCCESSES/%SUCCESSFUL RUNS VS. GAUSSIAN NOISE LEVEL, ALL CODES

dB	g(s) # %	g(h) # %	none # %	ham # %	QRC # %
0	0/0	0/0	0/0	0/0	0/0
1	2/1.0	0/0	0/0	0/0	0/0
2	19/9.6	3/1.5	0/0	0/0	7/3.6
3	62/31.5	26/13.2	0/0	2/1.3	35/17.6
4	122/61.3	72/36.9	1/0.5	7/3.6	107/53.8
5	175/87.9	140/71.0	2/1.0	41/20.6	177/88.9
6	194/97.5	186/93.5	7/3.5	92/46.2	194/97.5
7	197/99.0	194/97.5	31/15.6	149/74.9	198/99.5
totals	48.6%				45.2%

The line graph, Figure 13 on page 35 compares the percent success of each code in the Gaussian noise channel. For this figure of merit, the g(s) code outperforms both the g(h) and QRC, especially at S/N levels between 2-5 dB. The QRC outperforms g(h) at S/N levels between 2-7 dB.

The stacked bar comparison graph, Figure 14 on page 36 compares the overall success of each code, combining all S/N level runs. For total number of runs, g(s) out performs QRC by more than 50 successes.

C. CONSTANT BURST WIDTH CHANNEL

1. BER Results

Table 9 on page 37 represents BER exponents for 35, 200 superframe runs. Figure 15 on page 38 shows the BER performance recorded in table 9, with the area of critical code performance highlighted on the graph.¹⁵ The g(s)

¹⁵ From Table 4 page 21). INMARSAT Noise Burst Width: P(10 msec burst) = 0.80; P(10-40 msec burst) = 0.95.

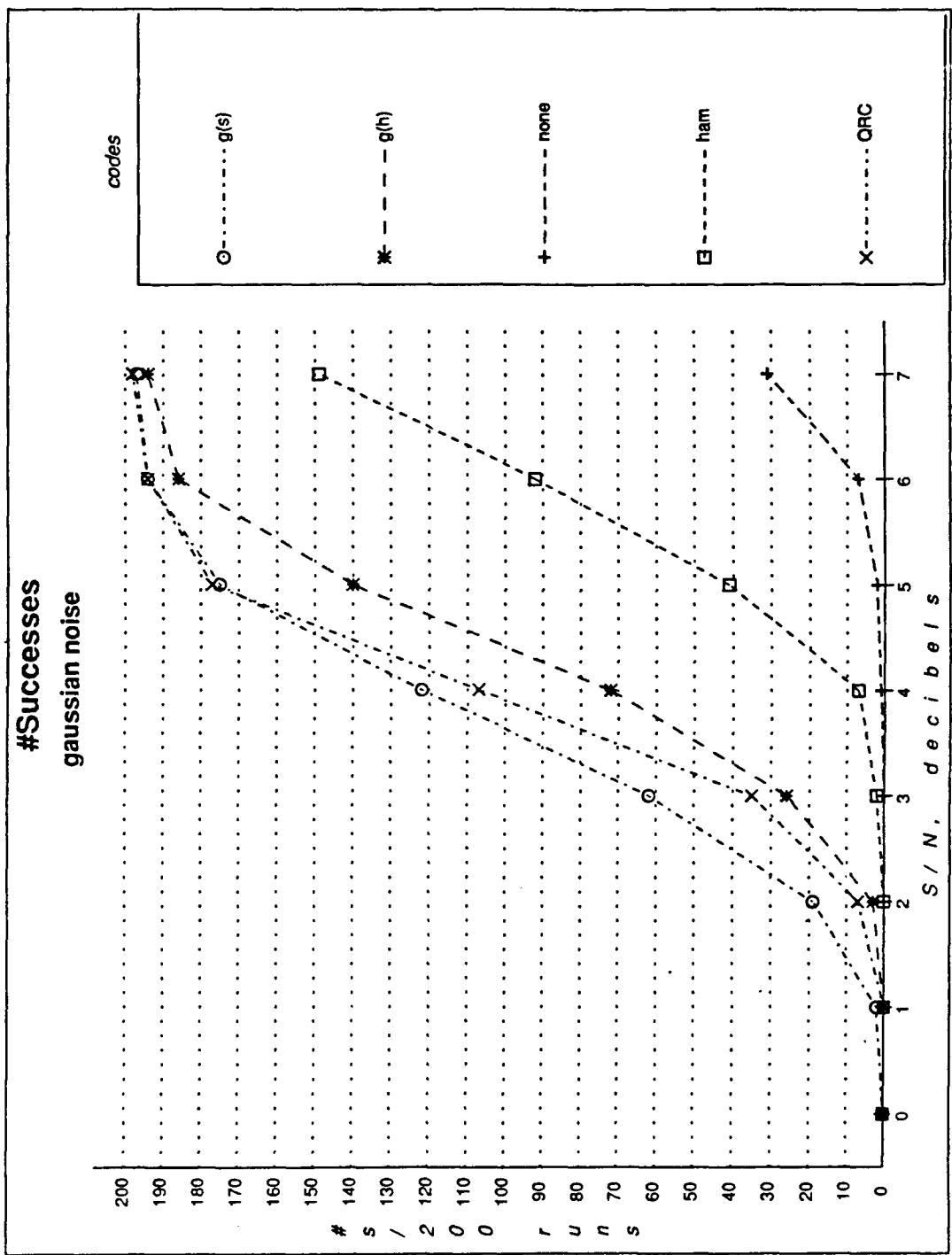


Figure 13. #Successes/%Successful for AWGN channel (line graph)

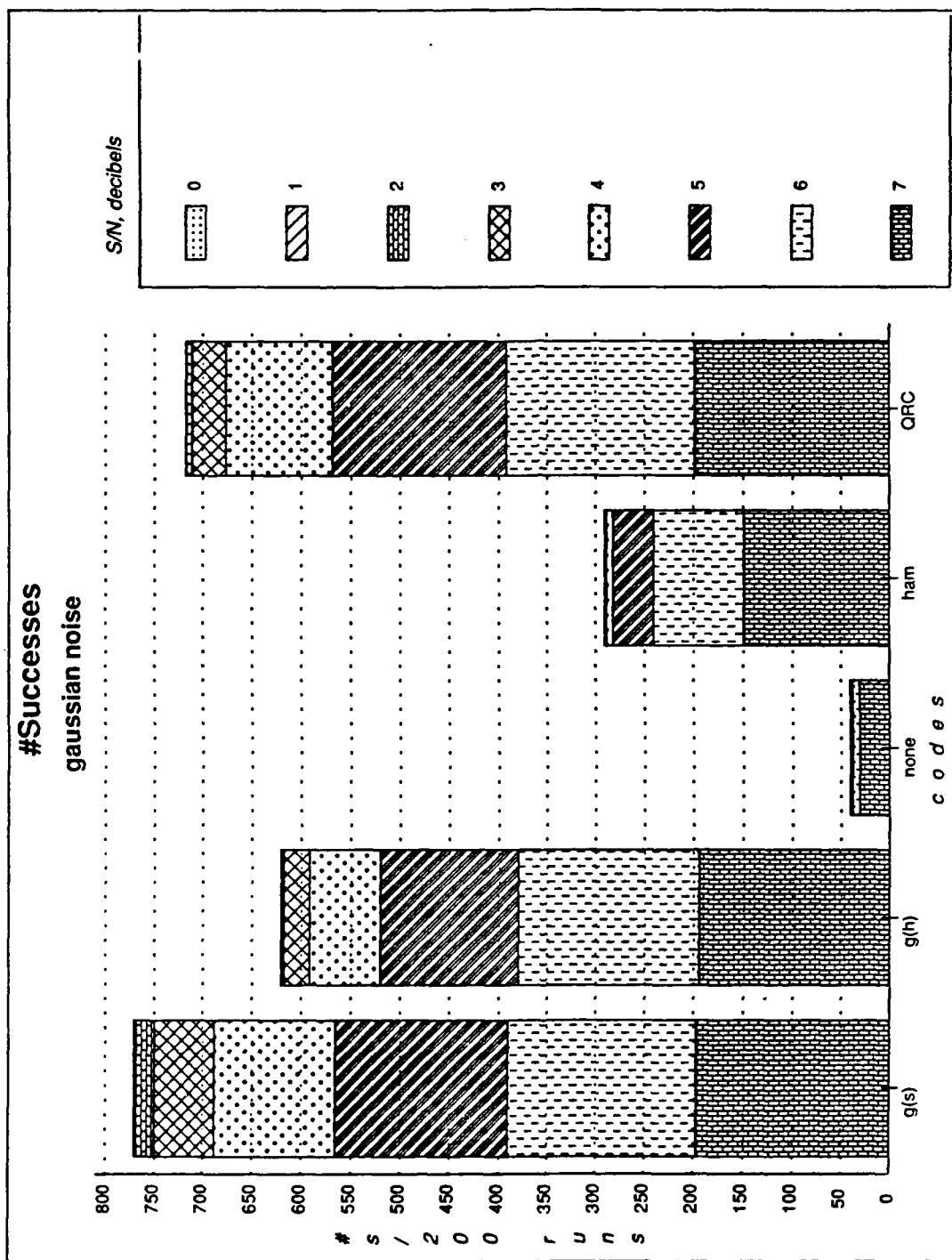


Figure 14. #successes/199 runs for AWGN channel (bar chart)

code outperforms the QRC at burst widths from 10-40 msec; the advantage diminishes at burst widths greater than 40 msec.

Table 9. BER AS A FUNCTION OF CONSTANT BURST WIDTHS, ALL CODES

burst widths	g(s)	g(h)	none	ham	QRC
5	-4.	-2.6021	-1.8297	-2.7375	-2.8447
10	-3.1759	-2.4461	-1.5331	-2.0706	-2.6716
20	-2.0301	-1.9281	-1.2612	-1.5567	-1.9431
40	-1.3516	-1.0516	-1.0419	-1.0956	-1.2048
100	-0.7595	-0.6655	-0.7721	-0.7022	-0.7404
200	-0.585	-0.5229	-0.5544	-0.5089	-0.5786
400	-0.4789	-0.4815	-0.5086	-0.4619	-0.5396

Figure 16 on page 39 also displays the effect that the varying burst widths have on each code. At the 20 msec burst width all three of the codes -- g(s), QRC, and g(h) -- begin to display a similar performance. For a 100 msec burst width condition, *all* codes perform equally poorly. Code response trends -- a consistent increase in the BER exponent as the burst width increases -- are as expected.

2. Run Success/Failure Results

Table 10 on page 40 displays the number and percent successful runs as function of constant burst widths, for all codes tested. At narrower levels of burst width, the g(s) code outperforms the other coded or uncoded channels. The advantage becomes less significant as the width of noise burst exceeds 20 msec. Again, the g(s) has the overall advantage of 4.9% more successful runs.

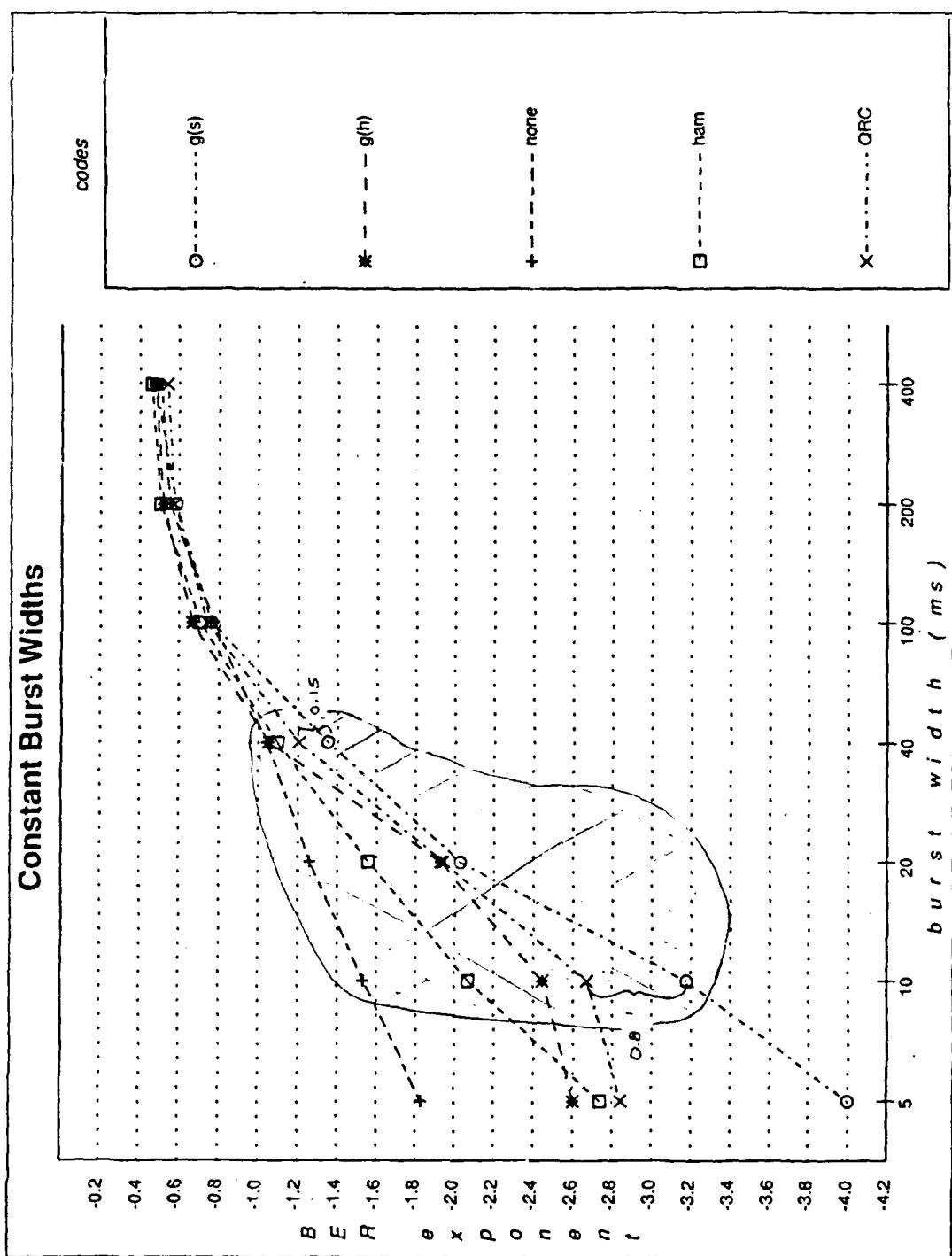


Figure 15. Constant Burst Width Performance (line graph)

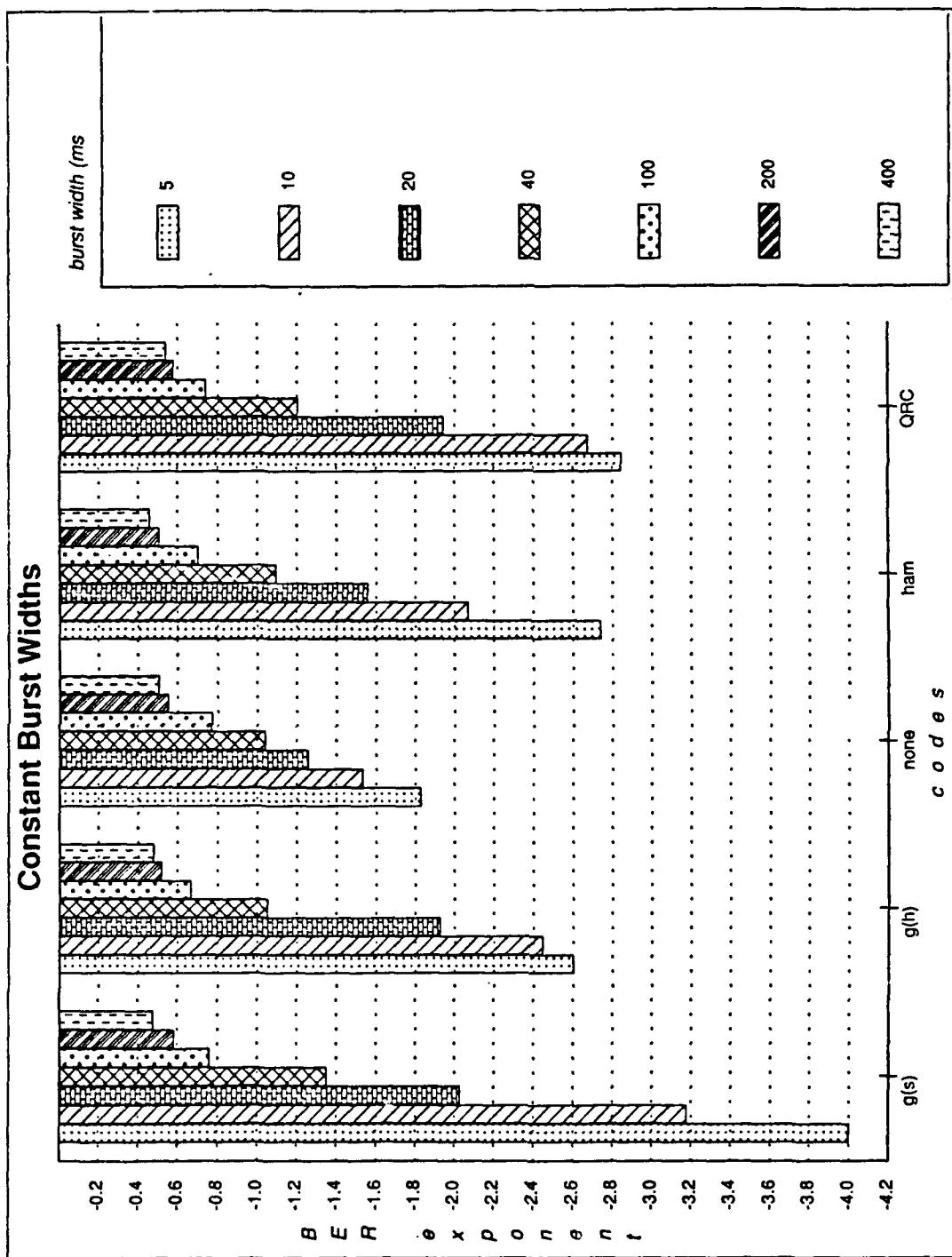


Figure 16. Constant Burst Width Performance (bar chart)

Table 10. #SUCCESSES/%SUCCESSFUL RUNS VS CONSTANT BURST WIDTHS, ALL CODES

burst widths	g(s) #/%	g(h) #/%	none #/%	ham #/%	QRC #/%
5	197/99.5	196/99.5	98/49.2	187/94.0	198/100
10	197/99.0	188/94.5	93/46.7	152/76.4	195/98.0
20	178/89.4	158/79.4	85/42.7	118/59.3	166/83.4
40	139/69.8	97/48.7	74/37.6	77/38.7	107/53.8
100	66/33.2	48/24.1	62/31.5	48/24.1	41/20.6
200	39/19.6	19/12.5	39/20.0	26/13.1	26/13.1
400	1/5.9	0,0	8/30.0	28/14.1	19/11.0
totals	59.7%				54.8%

The line graph, Figure 17 on page 41, compares the relative number of successes for each code. A more robust code with greater interleaver depth may be needed to satisfy performance objectives at these burst widths.¹⁶ The g(s) code performs best, but it's percent success degrades as burst widths exceed 40 msec. It is interesting to note that the uncoded channel surpasses all codes in performance except the g(s) for burst widths of 100 and 200 msec.

Figure 18 on page 42 also compares the percent success for each code. Again, the performance advantage of the g(s) and QR codes degrades beyond a 40 msec burst to the 100 msec burst. Figure 19 on page 43 shows the performance trends as burst widths lengthen. With the exception of the g(s) and QRC, all codes achieve less than 50% success at burst widths greater than or equal to 40 msec.

¹⁶ More analysis would be needed to reach a decisive conclusion.

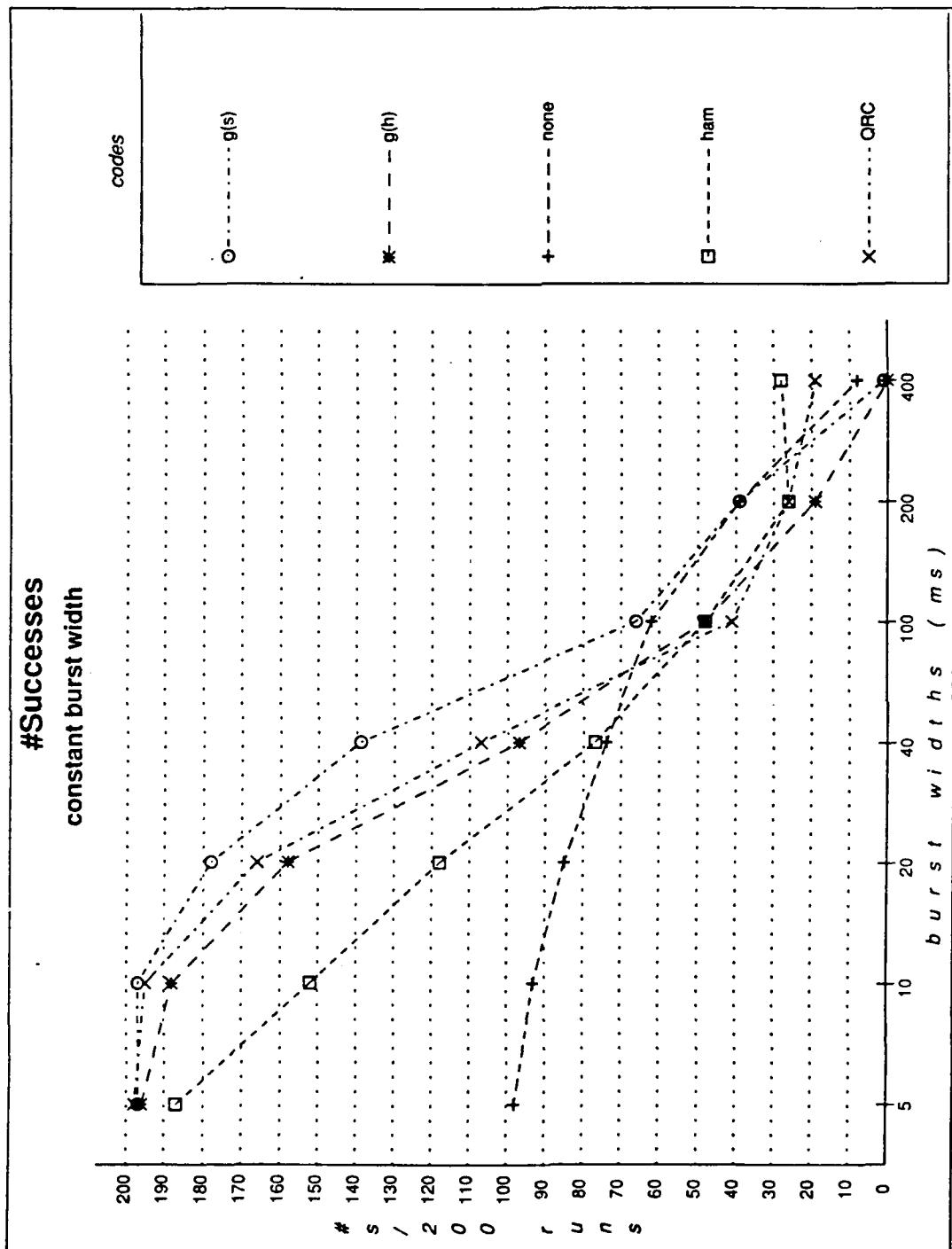


Figure 17. Constant Burst Width - S/F (line graph)

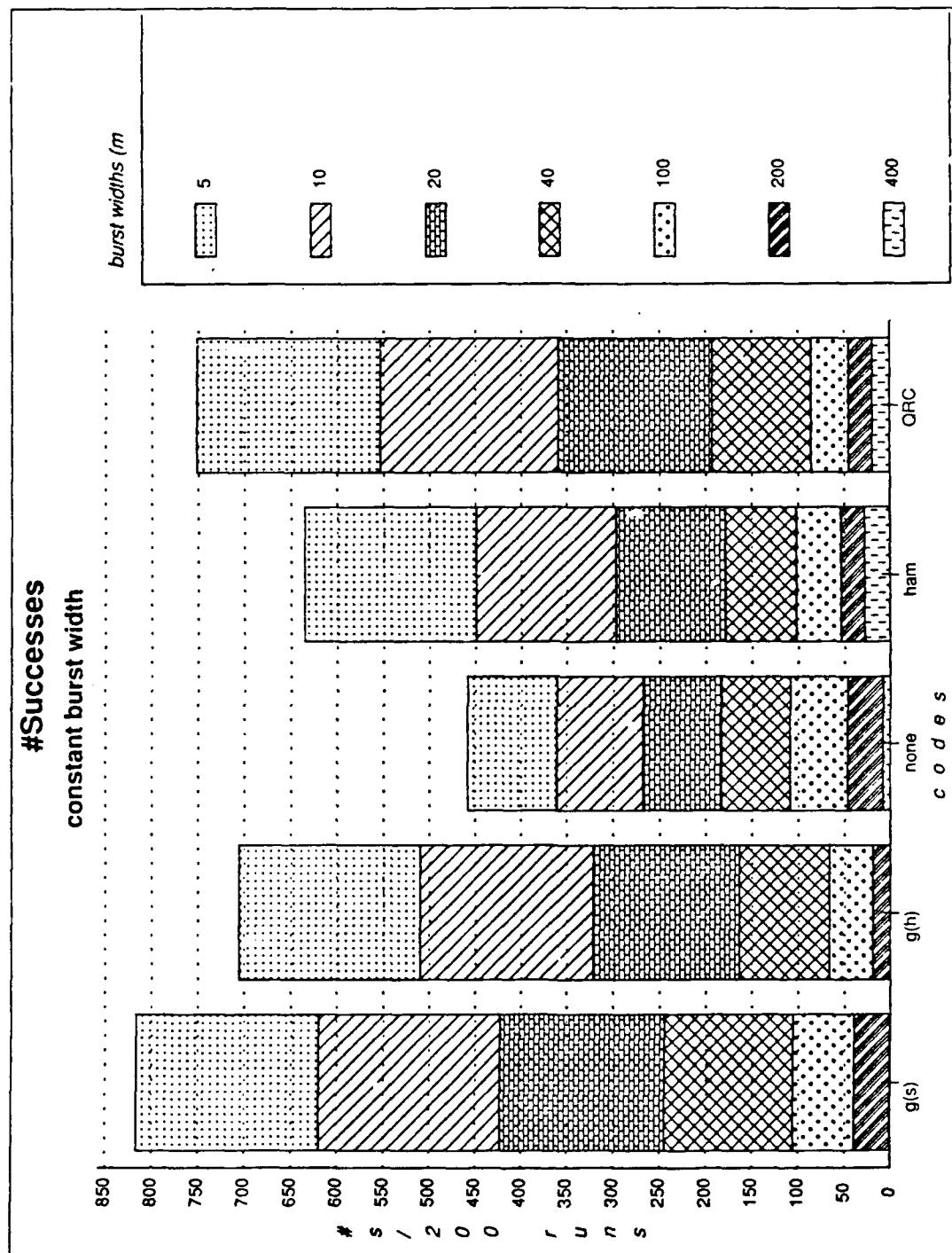


Figure 18. Constant Burst Width - S/F (bar chart)

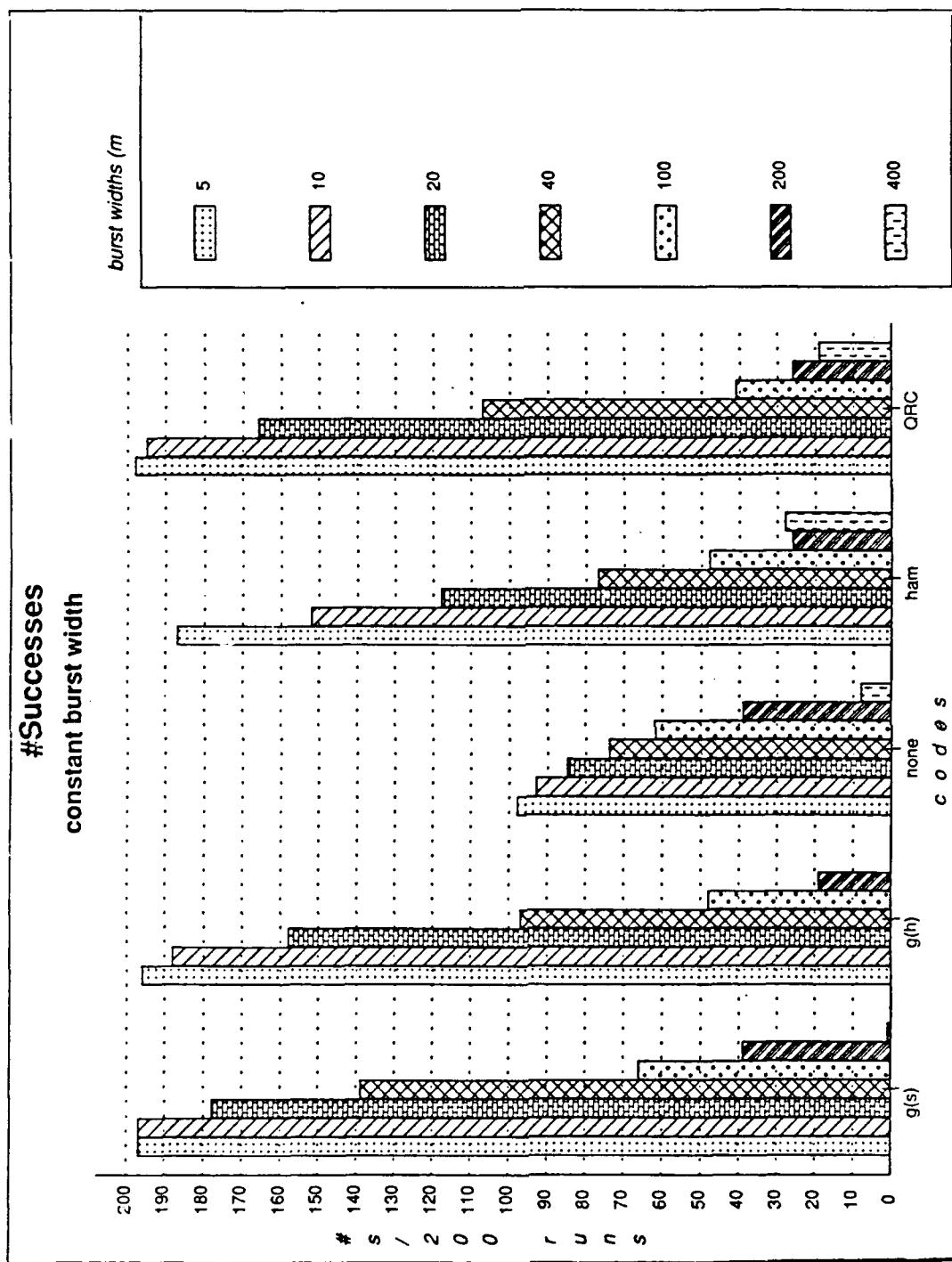


Figure 19. Constant Burst Width - S/F (comparison)

D. COMPARISON OF ERROR POSSIBILITIES

Given the larger codeword, by probabilistic calculations, the QRC leads in error correction capability since there are a greater number of possible errors corrected. See Figure 20 on page 45 for an understanding of the possibility of 6 errors corrected out of 48 bits for each code. Notice that the Golay calculation considers the hard decision number of possible errors only. The soft-decision Golay code yielded a 5% better success rate for the INMARSAT channel (see Table 6 page 28). It was also observed that the number of possible errors corrected is much closer to the QRC calculation - up to seven errors can be corrected per codeword.

In Chapter VI, the preceding results will be summarized and recommendations presented.

COMBINATIONS of 6 errors/48 bits corrected

QRC

$$62\% \times P(C(48,6),1) = 7,610,512$$

Golay

$$P(C(24,3),2) + C(24,3)C(2,2)P(C(24,3),0) = 4,096,576$$

24 bits

Hamming

$$P(C(8,1),6) + C(8,1)C(6,2)P(7,4) + \dots + C(8,1)C(6,6)P(7,0) = 159,944$$

8 bits

48 bits

Figure 20. Possible Errors Corrected

VI. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

A. CONCLUSIONS

Three simulated noise channels -- INMARSAT random burst, AWGN, and constant burst -- were used to analyze four EDAC codes; Golay hard decision, Golay soft decision, Hamming and QRC. Before the study commenced, the INMARSAT random burst channel model was determined to be the most realistic type of LMR noise channel. It was believed by NSA that the soft Golay and QRC codes would be very close performance competitors. The results obtained show that the soft decision Golay slightly outperforms the QRC based on the following:

- For the Gaussian channel, the BER exponent for the g(s) is significantly less than that of the QRC at S/N of 5 dB and below. The g(s) code also had greater percentage of successful runs than the QRC for S/N levels from 2-4 dB.
- For the Constant Burst Width channel, the g(s) marginally outperforms the QRC when subjected to 10 msec burst noise. For each code, percentage of successful runs is similar at this burst width; the g(s) achieves 1% greater success. Over all burst widths, the g(s) achieves 4.9% more successful superframe runs.
- For the INMARSAT random burst channel the results are very close. The QRC outperformed the g(s) by detecting and correcting 1.5% more errors and running almost 1% more successful superframes. For the additional 1000 superframe runs, the results are even closer. Since the performance margin is so close, the conclusion is that there is no significant difference between the two codes for this simulation. More superframe runs may further support this conclusion.

The margin of performance is very close, as expected, between the soft decision Golay and the QRC. The biggest disadvantage in QRC implementation versus soft decision Golay is the difficulty of algorithmic implementation and the larger number of codeword and parity combinations to choose from. This translates into greater processing time and greater memory storage.

Based on these two considerations, soft decision Golay is recommended as the best code for FS 1024.

B. RECOMMENDATIONS FOR FURTHER STUDY

1. Study Continuation

From experience it was learned that a more concentrated level of effort should have been paid to the 10-40 msec burst width region (95% of the burst fades for the INMARSAT PDF). More superframes should be subjected to these burst widths to provide more conclusive findings.

Also, additional INMARSAT channel iterations along with a statistical analysis¹⁷ may shed light on the difference that the long burst widths may have on the performance of the g(s) versus the QRC.

2. Implementation

Another consideration and topic for further study is the feasibility and architecture of hardware implementation of candidate EDAC algorithms. Several Digital Signal Processor (DSP) Integrated Circuits (ICs), such as the DSP32C and the TMS320C30, are being considered for hardware implementation. Microprocessor (assembly language) code of the soft decision Golay is already under development -- DIRNSA.¹⁸ Since the QRC codebook is much larger than the soft decision Golay, IC memory (itself limited by chip size) may be a limiting factor for hardware implementation of the QRC.

3. Other Codes

The scope of the thesis was narrowed to the four block codes; however, other possibilities should be considered in future studies. Simulation and testing of convolutional, other linear block, and concatenated codes may result in the discovery of an even better code for LMR application. A comparison of appropriate tradeoffs -- such as processing time, difficulty of algorithmic implementa-

¹⁷ The program must be modified to obtain the necessary statistical information, such as - the bit position of the error, position of the fade, the number of errors each fade caused, etc.

¹⁸ This EDAC was chosen as the code to protect the digitized voice (CELP processed) information bits.

tion, and code performance -- should be weighed in order to fairly judge the best code for the MI bits.

APPENDIX A: FORTRAN CODE

A. MAIN DRIVER

```
c 14*240=3360 bits per superframe (sf)
c 72+72=144 bits per mi
c 3360-144=3216 bits of fill per sf
c 3360/2=1680 bauds per sf

*****
c This program generates a superframme of 3360 bits.
c 72 bits are of interest in the detection and correction
c of errors. Three different EDAC schemes simmulated here
c for comparison of the best scheme under various conditions.
c The three codes are Golay (24,12) using soft and hard
c decision logic, Hamming (8,4), and Quadradic Residue Code
c (QRC)(48,24). Also, a run with no coding is performed as
c a control case.

c The entire superframe is interleaved, transmitted over a
c simulated AWGN channel, received, deinterleaved, and
c finally - checked for errors. The run is considered a
c failure if there are ANY errors.

c Options for the simmulated channel include variance of the
c s/n during non-fade (the fade s/n was held at -24.0 dB), and
c two burst modes. The first burst mode used the INMARSAT
c values of varying length from 10-200ms for LMR. The second
c burst mode allows for a constant burst length input.
*****

program mainedac

*****
Declarations*****

integer*4 tbaud(1680)
integer*4 fillbits(3216)
integer*4 parity(72)
integer*4 rbaud(1680)
integer*4 rbcnt,tbcnt,decodcnt1,decodcnt2
integer*4 modegolay,ham,parnum,qrc,sf,nummi
integer*4 index,prevoutdibit,table(16)
```

```

integer*4 tbits,bits,txbits,rbits
real xdisp,ydisp,confh,confl
real samples(3),noise,noisef,bprob,probq
integer*4 mode,iseed,vary
integer*4 testcnt,tbit(3360),rbit(3360),intlvtable(144)
integer*4 mibits(72),codeword(8),hmatrix(8),syndrometable(8)
integer*4 testcnt,paritybit
real intlvconf(3360),rcodeconf(144),rhashconf(144)
real rfillconf(3216)
real conf(24),gaus(256)
integer*4 code(144),hashcode(144),qrcbits(144),hambits(72)
integer*4 hashtable(144)
integer*4 rcode(144)
integer*4 itoterr,qrccwerr,qrcsferr,bwidth,myerror,hamerr
integer*4 iallerr, itotbitct
logical insync
integer*4 success,bits,fail,nerror,intlvrcnt,ifillrcnt,ihashrcnt
integer*4 rhashcode(144),rfillbits(3216)
integer*4 isym(2047)
integer*4 idata(24),kdata(24),ierr(5),qdata(48),hdata(4)
common /blk5/idata
common /blk7/conf,isym,kdata,ierr

```

*****DATA and TABLES*****

```

myerror = 0
data init,initfill /1,1/
data table /2,0,3,1,3,2,1,0,0,1,2,3,1,3,0,2/
if ((ham.eq.0).and.(qrc.eq.0)) then
  data hashtable /
1      1,25,49,73,97,121,2,26,50,74,98,122,
1      3,27,51,75,99,123,4,28,52,76,100,124,
1      5,29,53,77,101,125,6,30,54,78,102,126,
1      7,31,55,79,103,127,8,32,56,80,104,128,
1      9,33,57,81,105,129,10,34,58,82,106,130,
1      11,35,59,83,107,131,12,36,60,84,108,132,
1      13,37,60,85,109,133,
1      14,38,61,86,110,134,
1      15,39,62,87,111,135,
1      16,40,63,88,112,136,
1      17,41,64,89,113,137,
1      18,42,65,90,114,138,
1      19,43,66,91,115,139,
1      20,44,67,92,116,140,
1      21,45,68,93,117,141,

```

```

1      22,46,69,94,118,142,
1      23,47,70,95,119,143,
1      24,48,71,96,120,144/
end if

if (qrc.eq.1) then
  data hashtable /
1      1,49,97,2,50,98,3,51,99,4,52,100,
1      5,53,101,6,54,102,7,55,103,8,56,104,
1      9,57,105,10,58,106,11,59,107,12,60,108,
1      13,61,109,14,62,110,15,63,111,16,64,112,
1      17,65,113,18,66,114,19,67,115,20,68,116,
1      21,69,117,22,70,118,23,71,119,24,72,120,
1      25,73,121,26,74,122,27,75,123,28,76,124,
1      29,77,125,30,78,126,31,79,127,32,80,128,
1      33,81,129,34,82,130,35,83,131,36,84,132,
1      37,85,133,38,86,134,39,87,135,40,88,136,
1      41,89,137,42,90,138,43,91,139,44,92,140,
1      45,93,141,46,94,142,47,95,143,48,96,144/
end if

if (ham.eq.1) then
  data hashtable /
1      1,9,17,25,33,41,49,57,65,73,81,89,97,105,113,121,129,137,
1      2,10,18,26,34,42,50,58,66,74,82,90,98,106,114,122,130,138,
1      3,11,19,27,35,43,51,59,67,75,83,91,99,107,115,123,131,139,
1      4,12,20,28,36,44,52,60,68,76,84,92,100,108,116,124,132,140,
1      5,13,21,29,37,45,53,61,69,77,85,93,101,109,117,125,133,141,
1      6,14,22,30,38,46,54,62,70,78,86,94,102,110,118,126,134,142,
1      7,15,23,31,29,47,55,63,71,79,87,95,103,111,119,127,135,143,
1      8,16,24,32,30,47,56,64,72,80,88,96,104,112,120,128,136,144/
end if

c      read in table for golay decoder from disk file

open (3,file='isytab.dat',status='old',form='formatted')
read (3,20)isym
20  format(10(I6))
close(3)

c      read in gaussian distribution from disk file

open (4,file='gaussian.dat',status='old',form='formatted')
read (4,25)gaus
25  format(8(f6.0,1x))

```

```

close(4)

*****Interactive Input*****



write(6,*)'how many 420ms superframes would you like to run?'
read(5,*) sf
write(6,*)'what golay mode ? (1=soft,2=hard,3=nogolay) = ?'
read (5,*) modegolay
if(modegolay.eq.3)then
    write(6,*)'would you like to try the Hamming code?
*(1=yes,0=no) . . . '
    read(5,*) ham
    if(ham.eq.1) qrc=0
    if(ham.eq.0) then
        write(6,*)'would you like to perform a QRC error count?
*(1=yes,0=no) . . . '
        read(5,*) qrc
        end if
    else
        ham=0
        qrc=0
    end if
    write(6,*) 'what is s/n ratio in dB during fade = ? (real #)'
    c
        should be -24dB
    read (5,*) noisef
    write(6,*) 'what is s/n ratio in dB during no fade = ? (real #)'
    read (5,*) noise
    write(6,*) 'what is mode ? (0 for non-fading, 1 for fading) = '
    read (5,*) mode
    if(mode.eq.1)then
        write(6,*)'what is the time seed? (any positive integer) = '
        read (5,*) iseed
        write(6,*)'would you like to vary burst prob and width?
*(1=yes,0=no) . . . '
        read (5,*) vary
        if(vary.eq.1) then
            write(6,*)'what burst prob?(r .94056 INMARSAT) = '
            read (5,*) bprob
            write(6,*)'what burst width?(i 120=10ms, INMARSAT) = '
            read (5,*) bwidth
        end if
    else
        iseed = 1
    end if

```

```

***** write the superframe interleave table for the 144 codeword bits
***** only throughout frames 4 through 14 (frame 4 starts at bit 721)

    do 35 m=1,9
        do 30 mm=1,8
            intlvtable(((m-1)*16)+((mm-1)*2)+1)=
1                721+((m-1)*240)+((mm-1)*30)
            intlvtable(((m-1)*16)+((mm-1)*2)+2)=
1                721+((m-1)*240)+((mm-1)*30)+10)
30        continue
35        continue

***** Initialize ****

    itoterr = 0
    qrccsferr = 0
    qrccwcnt = 0
    success = 0
    fail = 0
    ifirst=1
    tbcnt=1680
    rbcnt=1680-10

***** Begin for sf# of superframes*****
***** don't start counting results until n=about 3 so that error counters
***** are in sync (test if insync and insyncfill .eq..true)

    do 500 n=1,sf
        c           loop for 1680 baud/sf - generate, tx, sim, rcv, etc.
        do 400 mk=1,1680
            tbcnt=tbcnt+1
            if(tbcnt.eq.1681)then
                tbcnt=1

        ***** fill mibits
            if(qrc.eq.1)nummi=72
            if(qrc.eq.0)nummi=36
        do 40 m=1,nummi
            call bitgen11(2,init,tbits)
            init=0
            if((qrc.eq.0).and.(ham.eq.0)) then
                mibits(((m-1)*2)+1)=0
                mibits(((m-1)*2)+2)=0
                if((tbits.eq.1).or.(tbits.eq.3))then
                    mibits(((m-1)*2)+1)=1

```

```

        end if
        if((tbits.eq.2).or.(tbits.eq.3))then
            mibits(((m-1)*2)+2)=1
        end if
    end if
    if(ham.eq.1) then
        hambits(((m-1)*2)+1)=0
        hambits(((m-1)*2)+2)=0
        if((tbits.eq.1).or.(tbits.eq.3))then
            hambits(((m-1)*2)+1)=1
        end if
        if((tbits.eq.2).or.(tbits.eq.3))then
            hambits(((m-1)*2)+2)=1
        end if
    end if
    if(qrc.eq.1) then
        qrcbits(((m-1)*2)+1)=0
        qrcbits(((m-1)*2)+2)=0
        if((tbits.eq.1).or.(tbits.eq.3))then
            qrcbits(((m-1)*2)+1)=1
        end if
        if((tbits.eq.2).or.(tbits.eq.3))then
            qrcbits(((m-1)*2)+2)=1
        end if
    end if
40    continue
    if (qrc.eq.1) go to 95

***** fill parbits
    if (ham.eq.1) parnum=18
    if ((ham.eq.0).and.(qrc.eq.0)) parnum=6
    call matrixgen(8,4,hmatrix,syndrometable)

    do 70 m=1,parnum
***** bit encoder for hamming
        if(ham.eq.1)then
            do 48 mm=1,2
                codeword(((mm-1)*2)+1)=hambits(((m-1)*4)
1                    +(((mm-1)*2)+1))
                codeword(((mm-1)*2)+2)=hambits(((m-1)*4)
1                    +(((mm-1)*2)+2))
                codeword(((mm-1)*2)+5)=0
                codeword(((mm-1)*2)+6)=0
48        continue
        call encodeham(8,4,hmatrix,paritybit,codeword)

```

```

***** load hamming codewords (parity + data) *****
      do 50 mm=1,8
          code(((m-1)*8)+mm)=codeword(mm)
50      continue
      else
***** generate parity bauds for golay here
      if (qrc.eq.0)then
          do 55 mm=1,6
              idata(((mm-1)*2)+1)=mibits(((m-1)*12)
1                  +(((mm-1)*2)+1))
1              idata(((mm-1)*2)+2)=mibits(((m-1)*12)
1                  +(((mm-1)*2)+2))
55      continue
      end if

      call golenc

      do 60 mm=1,12
          parity(((m-1)*12)+mm)=idata(12+mm)
60      continue
      end if
70      continue

***** load Golay and QRC codewords (bits)*****
      if((ham.eq.0).and.(qrc.eq.0)) then
          do 90 m=1,6
              do 80 mm=1,12
                  code(((m-1)*24)+mm)=mibits(((m-1)*12)+mm)
                  code(((m-1)*24)+mm+12)=parity(((m-1)*12)+mm)
80          continue
90          continue
      end if
95          continue
      if(qrc.eq.1) then
          do 97 m=1,144
              code(m)=qrcbits(m)
97          continue
      end if

***** scramble the codewords
      do 100 m=1,144
          hashcode(m)=code(hashtable(m))
100         continue
      do 110 m=1,1608

```

```

c      get the rest of the superframe's bits
c      call bitgen11fill(2,initfill,tbits)
c      same as bitgen11 but a separate routine

      initfill=0
      fillbits(((m-1)*2)+1)=0
      fillbits(((m-1)*2)+2)=0
      if((tbits.eq.1).or.(tbits.eq.3))then
          fillbits(((m-1)*2)+1)=1
      end if
      if((tbits.eq.2).or.(tbits.eq.3))then
          fillbits(((m-1)*2)+2)=1
      end if
110      continue

***** load the superframe with codewords and fill
      intlvcnt=1
      ihashcnt=1
      ifillcnt=1
      do 130 m=1,3360
          if(m.eq.(intlvtable(intlvcnt)))then
              tbit(m)=hashcode(ihashcnt)
              ihashcnt=ihashcnt+1
              intlvcnt=intlvcnt+1
          else
              tbit(m)=fillbits(ifillcnt)
              ifillcnt=ifillcnt+1
          end if
130      continue

***** bits to bauds
      do 140 m=1,1680
          if(tbit(((m-1)*2)+1).eq.0)then
              if(tbit(((m-1)*2)+2).eq.0)tbaud(m)=0
              if(tbit(((m-1)*2)+2).eq.1)tbaud(m)=2
          else
              if(tbit(((m-1)*2)+2).eq.0)tbaud(m)=1
              if(tbit(((m-1)*2)+2).eq.1)tbaud(m)=3
          end if
140      continue
      end if

      txbits=tbaud(mk)

***** differential phase encoding

```

```

        index=(4*txbits)+prevoutdibit
        txbit3=table(index+1)
        prevoutdibit=txbits

c***** transmit over simulated channel and receive
        call tx(txbits,samples)
        if(vary.eq.1)then
            call chsim(samples,noise,noisef,mode,iseed,gaus,
1                                bprob,bwidth)
        else
            call sim(samples,noise,noisef,mode,iseed,gaus,n,sf,mk)
        end if
        call rcv(samples,rbits,xdisp,ydisp,confh,conf1)

c***** The confidence calculations are used for softgolay only *****
        rbcnt=rbcnt+1
        rbaud(rbcnt-1)=rbits
        intlvconf(((rbcnt-2)*2)+1)=conf1
        intlvconf(((rbcnt-2)*2)+2)=confh
        if (rbcnt.eq.1681) then
            testcnt=testcnt+1
            rbcnt=1
            if (ifirst.eq.1) then
                ifirst=0
            else

c***** unpack and decode the bits and count any errors in the mi
c      this would be 18 calls to hamming or 6 calls to golay
c      if any of the 72 mi bits are in error then we fail and
c***** bauds to bits
            do 150 m=1,1680
                rbit(((m-1)*2)+1)=0
                rbit(((m-1)*2)+2)=0
                if((rbaud(m).eq.1).or.(rbaud(m).eq.3))
1                    rbit(((m-1)*2)+1)=1
                if((rbaud(m).eq.2).or.(rbaud(m).eq.3))
1                    rbit(((m-1)*2)+2)=1
150                continue

c***** deinterleave bits from the superframe
        intlvrcnt=1
        ihashrcnt=1
        ifillrcnt=1
        do 160 m=1,3360
            if(m.eq.(intlvtable(intlvrcnt)))then

```

```

        rhashcode(ihashrcnt)=rbit(m)
        rhashconf(ihashrcnt)=intlvconf(m)
        ihashrcnt=ihashrcnt+1
        intlvrcnt=intlvrcnt+1
    else
        rfillbits(ifillrcnt)=rbit(m)
        rfillconf(ifillrcnt)=intlvconf(m)
        ifillrcnt=ifillrcnt+1
    end if
160    continue

***** descramble the codeword bits
        do 170 m=1,144
            rcode(hashtable(m))=rhashcode(m)
            rcodeconf(hashtable(m))=rhashconf(m)
170    continue

***** decode the codewords (baud) ****
        if(qrc.eq.1)then
            decodcnt1=3
            decodcnt2=24
        end if
        if(ham.eq.1)then
            decodcnt1=18
            decodcnt2=2
        end if
        if((qrc.eq.0).and.(ham.eq.0))then
            decodcnt1=6
            decodcnt2=6
        end if
        do 200 m=1,decodcnt1
            if((ham.eq.0).and.(qrc.eq.0))then
                do 180 mm=1,24
                    idata(mm)=rcode(((m-1)*24)+mm)
                    conf(mm)=rcodeconf(((m-1)*24)+mm)
180        continue
            end if
            if(ham.eq.1)then
                do 181 mm=1,8
                    codeword(mm)=rcode(((m-1)*8)+mm)
                continue
181        end if
            if(qrc.eq.1)then
                do 182 mm=1,48

```

```

182
        qdata(mm)=rcode(((m-1)*48)+mm)
        continue
        end if

        if(modegolay.eq.1)call soft
        if(modegolay.eq.2)call hard
        if(ham.eq.1)then
            call decodeham(8,4,paritybit,myerror,hmatrix,
                           syndrometable,codeword)
&

c***** strip off the first 4 bits of each codeword MI bits.*****0
        do 183 mm=1,4
            hdata(mm)=codeword(mm)
        continue

        if(myerror.eq.1)then
            hamerr = hamerr + 2
            write(6,*)'decodeham detected errors '
            end if
        end if

c***** count errors in 72 MI bits (golay=12/24,hamming=4/8)
c          or all 144 bits (qrc=48/48)
c***** before the errors are counted they are changed to baud
c***** ****
qrccwerr=0
do 190 k=1,decodcnt2
    if((qrc.eq.0).and.(ham.eq.0))then
        if(idata(((k-1)*2)+1).eq.0)then
            if(idata(((k-1)*2)+2).eq.0)bits=0
            if(idata(((k-1)*2)+2).eq.1)bits=2
        else
            if(idata(((k-1)*2)+2).eq.0)bits=1
            if(idata(((k-1)*2)+2).eq.1)bits=3
        end if
    end if
    if(ham.eq.1)then
        if(hdata(((k-1)*2)+1).eq.0)then
            if(hdata(((k-1)*2)+2).eq.0)bits=0
            if(hdata(((k-1)*2)+2).eq.1)bits=2
        else
            if(hdata(((k-1)*2)+2).eq.0)bits=1
            if(hdata(((k-1)*2)+2).eq.1)bits=3
        end if
    End if

```

```

        if(qrc.eq.1)then
            if(qdata(((k-1)*2)+1).eq.0)then
                if(qdata(((k-1)*2)+2).eq.0)bits=0
                if(qdata(((k-1)*2)+2).eq.1)bits=2
            else
                if(qdata(((k-1)*2)+2).eq.0)bits=1
                if(qdata(((k-1)*2)+2).eq.1)bits=3
            end if
        end if
        call biterr11a(bits,2,insync,nerror)
        itoterr=itoterr+nerror
        if(qrc.eq.1)qrccwerr=qrccwerr+nerror
190      continue

***** This is the QRC BER counter section *****
c      errors/codeword are checked (for decodcnt1=3 cws)
c      QRC(48,24) will correct 5 errors/cw and 62.02% of the 6th errors
*****
        if(qrc.eq.1) then
            if(qrccwerr.eq.0)then
                write(6,*)'there were no errors in QRC cw'
            end if
            if((qrccwerr.le.5).and.(qrccwerr.gt.0)) then
                write(6,*)'# errors corrected = ',qrccwerr
                qrccwerr=0
            end if
            if(qrccwerr.eq.6)then
                probq = rand(0)
                if(probq.le..6202)then
                    write(6,*)'qrc 6th error corrected'
                    qrccwerr=0
                end if
            end if
            qrccsferr=qrccwerr+qrccsferr
        end if
195      continue
200      continue

***** print error results
c      if any errors in total error count , the run is a failure
*****
        if(qrc.eq.1) then
            itoterr = qrccsferr
            iallerr = iallerr + qrccsferr
            itotbitct = itotbitct + 144

```

```

        end if
        if(itoterr.eq.0)then
            success=success+1
            write(6,*)"success = ",success
        end if
        if(itoterr.ne.0)then
            fail=fail+1
            write(6,*)"fail = ",fail
            write(6,*)"total errors in sf = ",itoterr
        end if

***** reinitialize for new superframe *****
qrcsferr=0
itoterr=0
hamerr=0
if(.not.insync)then
    fail=0
    success=0
    testcnt=0
    itotbitct=0
    iallerr=0
end if

***** or use the fill bits to measure ber in non-fading noise
c
    call biterr11afill(bit,2,insyncfill,nerror)

        end if
        end if
400    continue
        write(6,*) ' you just completed superframe # ',n
        if((qrc.eq.1).and.(mod(n,50).eq.0))write(6,*)
1        'iallerr= ',iallerr,' itotbitct= ',itotbitct,
1        'n = ',n
500    continue

***** print final counts and results
        write(6,*)" the total number of failures = ",fail
        write(6,*)" the total number of successes = ",success
        if(modegolay.eq.1) write(6,*)" This was a soft golay run"
        if(modegolay.eq.2) write(6,*)" This was a hard golay run"
        if(modegolay.eq.3) write(6,*)" This was a nogolay run"
        if(ham.eq.1)write(6,*)" This was a Hamming run"
        if(qrc.eq.1)write(6,*)" This was a QRC BE count run"
        write(6,*)" This run used fading (1=yes,0=no) ",mode
        if(vary.eq.1)write(6,*)"fading width, bwidth = ",bwidth

```

```
write(6,*)' s/n during fade (dB) = ',noisef
write(6,*)' s/n during non-fade (dB) = ',noise
c*****QUIT!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
end
```

B. SUBROUTINES

```
C*****  
  
subroutine biterr11a(data,nbits,insync,nerror)  
  
    integer*4 data, nbits, nerror, rxdata, shindex, error  
    integer*4 index, errcnt, bitcnt, i, itemp  
    integer*4 nblk, btest, lshift, rshift, xor  
    logical insync  
    data errcnt, bitcnt / 0, 0 /  
    data rxdata, index / 0, 1 /  
    data nblk /100/  
  
    rxdata = rshift(rxdata,nbits)  
    call mvbits(data,0,nbits,rxdata,11-nbits)  
  
    shindex = lshift(index,2)  
    itemp = xor(index,shindex)  
    index = rshift(index,nbits)  
    call mvbits(itemp,2,nbits,index,11-nbits)  
  
    nerror = 0  
    error = xor(index,rxdata)  
    if (error .ne. 0) then  
        do 9 i =11-nbits, 10  
            if (btest(error,i).eq.1) nerror = nerror +1  
9         continue  
    end if  
  
    errcnt = errcnt + nerror  
    bitcnt = bitcnt + nbits  
  
    if (insync) then  
        if (bitcnt .ge. nblk) then  
            if (float(errcnt) .gt. .35 * float(bitcnt)) then  
                insync = .false.  
                nblk=100  
            else  
                write(6,*) 'errors in ',nblk, ' bits = ', errcnt  
                nblk=3000  
c                to span fades  
                errcnt = 0  
                bitcnt = 0  
            end if
```

```

        end if
    end if

    if (.not. insync) then
        if (bitcnt .ge. 20) then
            if (float(errcnt) .le. .2 * float(bitcnt)) then
                insync = .true.
            write(6,*) 'insync = true'
            else
                if (bitcnt.eq.20) write(6,*) 'not yet in sync'
                    index = rxdata
                    if (index .eq. 0) index = 1
                end if
                errcnt = 0
                bitcnt = 0
            end if
        end if
    end if

    return
end

```

c-----

```

subroutine biterr11afill(data,nbits,insync,nerror)

integer*4 data, nbits, nerror, rxdata, shindex, error
integer*4 index, errcnt, bitcnt, i, itemp
integer*4 nblk, btest, lshift, rshift, xor
logical insync
data errcnt, bitcnt / 0, 0 /
data rxdata, index / 0, 1 /
data nblk /100/

rxdata = rshift(rxdata,nbits)
call mvbits(data,0,nbits,rxdata,11-nbits)

shindex = lshift(index,2)
itemp = xor(index,shindex)
index = rshift(index,nbits)
call mvbits(itemp,2,nbits,index,11-nbits)

nerror = 0
error = xor(index,rxdata)
if (error .ne. 0) then
    do 11 i =11-nbits, 10
        if (btest(error,i).ne.0) nerror = nerror +1

```

```

11      continue
end if

errcnt = errcnt + nerror
bitcnt = bitcnt + nbits

if (insync) then
  if (bitcnt .ge. nblk) then
    if (float(errcnt) .gt. .35 * float(bitcnt)) then
      insync = .false.
nblk=100
    else
write(6,*) 'errors in ',nblk, ' bits = ', errcnt
nblk=3000
c          to span fades
  errcnt = 0
  bitcnt = 0
  end if
end if
end if

if (.not. insync) then
  if (bitcnt .ge. 20) then
    if (float(errcnt) .le. .2 * float(bitcnt)) then
      insync = .true.
write(6,*) 'insync = true'
    else
      if (bitcnt.eq.20) write(6,*) 'not yet in sync'
        index = rxdata
        if (index .eq. 0) index = 1
      end if
      errcnt = 0
      bitcnt = 0
    end if
  end if
end if

return
end

```

```

*****

```

```

function btest(i1,i2)

C ***  this function returns 1 if bit position a2 of a1 is 1 and
c ***          returns 0 if bit position a2 of a1 is 0

```

```

integer*4 t1,t2,btest,i1,i2

t1=i1
t2=i2
t1 = rshift(t1,t2)
t1 = and(t1,1)
btest = t1

return
end

```

```
C*****
```

```

subroutine mvbits(isource,ibitfrom,length,idest,ibitto)

integer*4 isource, ibitfrom, length, idest, ibitto, n
integer*4 k, ks, btest, xor, lshift

do 12 n = 1, length

k = ibitto + n - 1
ks = lshift(1,k)

if (btest(isource,(ibitfrom+n-1)).ne.0) then
c **set**
      if (btest(idest,k).eq.0)
      1           idest = xor(idest,ks)
c **clear**
      else
        if (btest(idest,k).ne.0)
      1           idest = xor(idest,ks)
      end if
12    continue

return
end

```

```
C-----
```

```

c      soft decision decoder for golay(24,12)
c      uses chase ii algorithm with table look-up decoder

subroutine soft

```

```

common/blk5/idata
common/blk7/conf,isym,kdata,ierr
integer*4 idata(24),kdata(24),ierr(5)
  integer*4 isym(2047)
integer*4 nb(4),mask(4,24),jb(16,24),ib(24),nerr
  real conf(24)

  nerr=1
C
C

c   w is analog weight of most likely error pattern
c   set w initially to a very large value
w=10000000.0

c   identify 4 bits with lowest confidence values
call low4(nb)
wgt4=0.

c   gen 4 masks identifying 4 bits
call mgen(mask,nb)

c   gen 2**4=16 patterns
call patgen(mask,jb)

c   test each of 16 patterns for the SOFT decoder
do 19 i=1,16

c     clear ierr
c     do 13 j=1,5
c       ierr(j)=0
13   continue

c     add data and test error pattern, store in kdata
c     do 14 j=1,24
c       call exor(kdata(j),idata(j),jb(i,j))
14   continue

c     binary decoder
c     accepts input data in kdata
c     returns data uncorrected
c     returns no. of errors in ierr(5)
c     returns location of errors in ierr(1) to ierr(4)

```

```

call golay

c      test if decoded word was error free
c      if (ierr(5).eq.0) then
c          test word was error free
c          accept test word as best estimate
c          w=0.0

          do 15 j=1,24
              idata(j)=kdata(j)
15      continue
      return
      else
c          test word contained errors
c          get final error pattern, calculate its analog wgt
c          wgt=0.0
c          n=ierr(5)

c          add detected errors to test error pattern
c          do 16 j=1,n
c              ix=ierr(j)
c              call exor(jb(i,ix),jb(i,ix),nerr)
16      continue

          do 17 j=1,24
              if(jb(i,j).eq.1)wgt=wgt+conf(j)
17      continue

c          compare wgt and w
c          save error pattern with lowest analog weight

          if(wgt.lt.w)then
c              store new value
c              save error pattern
c              w=wgt
c              do 18 j=1,24
c                  ib(j)=jb(i,j)
18          continue

          end if
      end if
19      continue

c      decode data with most likely error pattern
      do 21 i=1,24
          call exor(idata(i),idata(i),ib(i))

```

```

21      continue

      return
      end

c-----
c      hard decision decoder for golay(24,12)
c      uses chase ii algorithm with table look-up decoder

      subroutine hard

      integer*4 idata(24),kdata(24),ierr(5)
      integer*4 isym(2047)
      integer*4 nb(4),mask(4,24),jb(16,24),ib(24),nerr
      real conf(24)
      common/blk5/idata
      common/blk7/conf,isym,kdata,ierr

      nerr=1

c      w is analog weight of most likely error pattern
c      set w initially to a very large value
c      w=1000000.0

c      identify 4 bits with lowest confidence values
      call low4(nb)
      wgt4=0.

c      gen 4 masks identifying 4 bits
      call mgen(mask,nb)

c      gen 2**4=16 patterns
      call patgen(mask,jb)

c      test 1 pattern --> hard
      do 28 i=1,1

c      clear ierr
      do 22 j=1,5
          ierr(j)=0
22      continue

c      add data and test error pattern, store in kdata
      do 23 j=1,24

```

```

        call exor(kdata(j),idata(j),jb(i,j))
23    continue

c      binary decoder
c      accepts input data in kdata
c      returns data uncorrected
c      returns no. of errors in ierr(5)
c      returns location of errors in ierr(1) to ierr(4)

        call golay

c      test if decoded word was error free
c      if (ierr(5).eq.0) then
c          test word was error free
c          accept test word as best estimate
c          w=0.0

        do 24 j=1,24
            idata(j)=kdata(j)
24    continue

        return
        else
c          test word contained errors
c          get final error pattern, calculate its analog wgt
c          wgt=0.0
c          n=ierr(5)

c          add detected errors to test error pattern
c          do 25 j=1,n
c              ix=ierr(j)
c              call exor(jb(i,ix),jb(i,ix),nerr)
25    continue

        do 26 j=1,24
            if(jb(i,j).eq.1)wgt=wgt+conf(j)
26    continue

c      compare wgt and w
c      save error pattern with lowest analog weight

        if(wgt.lt.w)then
c          store new value
c          save error pattern
c          w=wgt
        do 27 j=1,24

```

```

                ib(j)=jb(i,j)
27        continue
        end if
    end if
28    continue

c      decode data with most likely error pattern
do 29 i=1,24
    call exor(idata(i),idata(i),ib(i))
29    continue

    return
end

c-----
subroutine low4(nb)

c      to identify in nb the location of 4 lowest conf values
dimension d(4)
integer*4 kdata(24),ierr(5),nb(4)
integer*4 isym(2047)
real conf(24)
common/blk7/conf,isym,kdata,ierr

c      assume first 4 are lowest

do 31 i=1,4
    d(i)=conf(i)
    nb(i)=i
31    continue

c      compare remaining values
do 33 i=5,24
    a=conf(i)
    n=i
    j=1
    if (j.gt.4) go to 33
        if (a.lt.d(j)) then
            a is < d(j)
            c      replace d(j) with a
            c      save d(j) to compare with other values in d
            c      save nb(j)
            b=d(j)
            nx=nb(j)

```

```

c           replace
c           d(j)=a
c           nb(j)=n
c           rename the saved values
c           a=b
c           n=nx
c           j=1
c           end if
c           incr j
c           j=j+1
33      continue

57      return
end

c-----
c      mask generator for soft decision golay decoder
c      generate 4 masks with 1 bit in location nb(i)

subroutine mgen(mask,nb)

dimension mask(4,24),nb(4)
integer*4 mask,nb

do 35 i=1,4
  do 34 j=1,24
    mask(i,j)=0
34      continue
    n=nb(i)
    mask(i,n)=1
35      continue

return
end

c-----
c      generate 16 patterns based on 4 bits

subroutine patgen(mask,jb)

integer*4 mask(4,24),jb(16,24)

do 36 i=1,24

```

```

jb(1,i)=0
jb(2,i)=mask(1,i)
jb(3,i)=mask(2,i)
jb(4,i)=mask(3,i)
jb(5,i)=mask(4,i)
jb(6,i)=jb(2,i)+mask(2,i)
jb(7,i)=jb(2,i)+mask(3,i)
jb(8,i)=jb(2,i)+mask(4,i)
jb(9,i)=jb(3,i)+mask(3,i)
jb(10,i)=jb(3,i)+mask(4,i)
jb(11,i)=jb(4,i)+mask(4,i)
jb(12,i)=jb(6,i)+mask(3,i)
jb(13,i)=jb(6,i)+mask(4,i)
jb(14,i)=jb(7,i)+mask(4,i)
jb(15,i)=jb(9,i)+mask(4,i)
jb(16,i)=jb(12,i)+mask(4,i)
36    continue

do 56 j=1,16
    do 37 i=1,24
        jb(j,i)=and(jb(j,i),1)
37    continue
56    continue

return
end

c-----
c      exclusive or of two integer*4s
c      one bit per integer*4

subroutine exor(i,j,k)

integer*4 i,j,k

i=and(j+k,1)

return
end

c-----
c      binary table look-up decoder for golay (24,12) code

```

```

subroutine golay

integer*4 idata(24),ierr(5),kdata(24),is(11)
integer*4 isym(2047)
real conf(24)
common/blk5/idata
common/blk7/conf,isym,kdata,ierr

n=23
ierr(5)=0

c      generate syndrome
c      write(6,*) 'generating golay syndrome'
call encode(kdata,is,n)

c      use syndrome to generate index to table
ir=0
do 38 j=1,11
    ir=ir*2+is(j)
38 continue

if(ir.ne.0)then
    c      look up error pattern
    c      possibility of up to 3 errors
    c      recorded as three 5-bit symbols in a 16-bit word
    ix=isym(ir)
    c      identify error locations and count errors
    do 39 j=1,3
        ierr(j)=and(ix,31)
        if(ierr(j).gt.0)ierr(5)=ierr(5)+1
        ix=ix/32
    c      if(ierr(j).gt.0)write(6,*)'ierr(j)=',ierr(j)
39 continue
end if

c      test overall parity
ir=ierr(5)
do 41 j=1,24
    ir=ir+kdata(j)
41 continue

ir=and(ir,1)

c      test for even parity
if (ir.ne.0) then

```

```

c      parity check failed
c      force overall parity
c      increment error count
c      ir=ierr(5)+1
c      ierr(ir)=24
c      ierr(5)=ir
end if

      return
end

c-----
c      golay(23,12) encoder, syndrome generator

subroutine encode(idata,ip,n)

integer*4 idata(12),ip(11),ix

c      g(x)=x**11+x**9+x**7+x**6+x**5+x+1
c      clear ip
do 42 i=1,11
      ip(i)=0
42  continue

c      read in n bits
do 43 i=1,n
      call exor(ix,idata(i),ip(1))
      ip(1)=ip(2)
      call exor(ip(2),ix,ip(3))
      ip(3)=ip(4)
      call exor(ip(4),ix,ip(5))
      call exor(ip(5),ix,ip(6))
      call exor(ip(6),ix,ip(7))
      ip(7)=ip(8)
      ip(8)=ip(9)
      ip(9)=ip(10)
      call exor(ip(10),ix,ip(11))
      ip(11)=ix
43  continue

      return
end

c-----

```

```

subroutine bitgen11(nbts,ival,data)

c this routine generates a pseudorandom sequence of bits using an 11 bit
c shift register, exoring the 9th and 11th bits to generate the new 1st bit
c before shifting. the length of the pseudorandom sequence is (2**11)-1
c or 2047 bits.

integer*4 data, shindex, nbts, ival, index, temp
integer*4 lshift, rshift, xor

if (ival .gt. 0 .and. ival .lt. 2048) index = ival

data = 0
c ensure that all bits in data are 0

call mvbits(index,0,nbts,data,0)
c move bits from index to data

shindex = lshift(index,2)
c shindex is index shifted left 2

temp = xor(index,shindex)
c temp contains new bits for index

index = rshift(index,nbts)
c shift index right by nbts

call mvbits(temp,2,nbts,index,11-nbts)
c move new bits, temp to index

return
end

c-----
c  golay encoder

subroutine golenc

integer*4 idata(24),id(12),is(11)
common/blk5/idata

n=12

```

```

c load 12 information bits
c sum inf bits for overall parity
do 44 j=1,12
    id(j)=idata(j)
44    continue

c encode using n-k type shift register
call encod(id,is,n)

c store parity bits in same array as inf bits
do 45 j=1,11
    idata(j+12)=is(j)
45    continue

c generate over all parity bit(even parity)
c store as 24th bit in array
    m=0

    do 46 j=1,23
        m=m+idata(j)
46    continue

idata(24)=and(m,1)

return
end

c-----
c golay(23,12) encoder, syndrome generator
c x11+x9+x7+x6+x5+x+1

subroutine encod(idata,ip,n)
integer*4 idata(12),ip(11),ix

c clear ip
do 47 i=1,11
    ip(i)=0
47    continue

c read in n bits
do 48 i=1,n
    call exor(ix,idata(i),ip(1))
    ip(1)=ip(2)
    call exor(ip(2),ix,ip(3))

```

```

ip(3)=ip(4)
call exor(ip(4),ix,ip(5))
call exor(ip(5),ix,ip(6))
call exor(ip(6),ix,ip(7))
ip(7)=ip(8)
ip(8)=ip(9)
ip(9)=ip(10)
call exor(ip(10),ix,ip(11))
    ip(11)=ix
48    continue

return
end

c-----
subroutine bitgen11fill(nbites,ival,data)

c this routine generates a pseudorandom sequence of bits using an 11 bit
c shift register, exoring the 9th and 11th bits to generate the new 1st bit
c before shifting.  the length of the pseudorandom sequence is (2**11)-1
c or 2047 bits.

integer*4 data, shindex, nbites, ival, index, temp
integer*4 lshift, rshift, xor

if (ival .gt. 0 .and. ival .lt. 2048) index = ival

data = 0
c ensure that all bits in data are 0

call mvbits(index,0,nbites,data,0)
c move bits from index to data

shindex = lshift(index,2)
c shindex is index shifted left 2

temp = xor(index,shindex)
c temp contains new bits for index

index = rshift(index,nbites)
c shift index right by nbites

call mvbits(temp,2,nbites,index,11-nbites)
c move new bits, temp to index

```

```

    return
end

c -----
subroutine tx(dibit,txsamp)

dimension txbuff(32), txsamp(3)
integer*4 dibit, index, i
real txbuff, txsamp
data txbuff, index / 32*0., 1 /

call modulate(dibit,index,txbuff)
c modulate one baud or symbol

c add symbol to transmit buffer
c note : each symbol is filtered by the modulator to be wider than
c one baud so as to restrict the bandwidth to about 4000 Hz for
c reduction of ACI (adjacent channel interference), so that the resulting
c baud pulses overlap and must be added together

do 49 i = 1, 3
  txsamp(i) = txbuff(index)
  txbuff(index) = 0
  index = mod(index,32) + 1
49 continue

return
end

c -----
subroutine modulate(mbit,index,buffer)

integer*4 mbit, phasel, cphase, tphase
integer*4 point, wlength, i, index, modangle
real s, pi, buffer, w
dimension phasel(4), w(29), buffer(*)

data phasel / 225,135,315,45 /
data wlength, modangle, cphase, pi / 29, 0, 0, 3.141593 /

c this is the transmit window to shape the output spectrum to about
c 4000 Hz wide

```

```

    data w / -.005696,.062601,.028191,-.021020,-.060997,
*   -.035666,.049659,.106424,.043728,-.114226,-.203894,
*   -.049151,.358925,.805832,.999756,.805832,.358925,
*   -.049151,-.203894,-.114226,.043728,.106424,.049659,
*   -.035666,-.060997,-.021020,.028191,.062601,-.005696/

    modangle = phasec(mbit + 1)
c modulation phase change angle

    cphase = mod(cphase + 270, 360)
c continuous unmodulated carrier phase

    tphase = mod(cphase + modangle, 360)
c actual transmit phase

    point = index

c take the sine wave of the actual transmit phase and window it
    do 51 i = 1, wlength
        s = .364 * w(i) * sin(pi / 180. * (tphase + 90 * i))
        buffer(point) = buffer(point) + s
        point = mod(point, 32) + 1
51    continue

    return
end

c -----
subroutine rcv(samples,dbits,xdisp,ydisp,confh,conf1)

c , purpose: this routine demodulates an 8000 b/s 4 phase dpsk modem signal.
c           it is called once to demodulate each baud.

c inputs:  signin - contains samples of the signal to be demodulated.
c           signin(1) is first in time.

c outputs: dbits - an integer which contains the 2 demodulated bits.
c           The data is stored in the least significant bits;
c           the lsb is first in time.

c brief description of subroutine functions:

c equalize -   calculates the output of the adaptive equalizer.
c decode -     uses the equalizer output to determine the data bits.

```

```

c           a phase reference is calculated for internal use.

      integer*4 dbits, i
      real confh,conf1
      real signal, x, y
      real xdisp,ydisp
      real signal(48), samples(3)
      real xcoef(48),ycoef(48)

      common /adequ/ xcoef, ycoef

c compromise equalizer coefficients for removing the intersymbol
c interference introduced by the transmitter windowing :
data xcoef / 0.00047277, 0.00018969, 0.00152612,-0.00026510,
1 0.00288611,-0.00077746, 0.00057433,-0.00176436,
1 -0.00299245,-0.00031443,-0.01333420, 0.00245006,
1 0.00073868, 0.00575836, 0.00552585, 0.00128170,
1 0.01571514,-0.00732426, 0.00609350,-0.01291209,
1 -0.03999998,-0.00832545,-0.10446436, 0.00526107,
1 -0.14213182, 0.01429809, 0.38911167, 0.03028025,
1 -0.06119568, 0.01810114,-0.00429513, 0.00713205,
1 0.01294118, 0.00074462, 0.00006572, 0.00038059,
1 -0.01742128, 0.00060559,-0.00858223, 0.00059077,
1 0.00697080,-0.00119318, 0.00344639,-0.00073849,
1 0.00324149,-0.00039312, 0.00125349,-0.00045128/
data ycoef / -0.00016221, 0.00070496,-0.00036193,-0.00072445,
1 -0.00059857,-0.00178603,-0.00014448,-0.00418214,
1 0.00070030, 0.00100549, 0.00305764, 0.00433583,
1 0.00079199, 0.00792035,-0.00374299, 0.01238339,
1 -0.00632491,-0.01299071, 0.00042162,-0.03951978,
1 0.01424530,-0.02844719, 0.02507262, 0.05758527,
1 0.02317356, 0.35042825, 0.01940719,-0.24283291,
1 -0.00569436,-0.01806669,-0.01134070,-0.00663402,
1 -0.00711616,-0.02175912,-0.00075.78,-0.01645218,
1 0.00256463,-0.00212019, 0.00016785, 0.02115092,
1 -0.00076241, 0.00839603,-0.00143184,-0.00148724,
1 -0.00056496,-0.00391606,-0.00031074,-0.00173826/

      data signal / 48*0.0 /

c signal buffer is as long as the equalizer that it will multiply against
c or 48 samples long

      do 52 i = 1, 45
c           shift signal buffer to accomodate new samples

```

```

        signal(i) = signal(i+3)
52    continue

        do 53 i = 46, 48
c          put new samples into signal buffer
          signal(i) = samples(i-45)
53    continue

        call equalize(signal,x,y)

        call decode(x,y,dbits,xdisp,ydisp,confh,conf1)

        return
        end

c-----
subroutine equalize(signal,x,y)

c purpose: this routine generates the output of the equalizer; i.e., it
c           calculates the output value of each fir equalizer filter.

c input:   signal - a real array which contains the received signal samples.
c           signal(1) is first in time.

c outputs: x - the x-coordinate of the equalizer output.
c           y - the y-coordinate of the equalizer output.

        integer*4 i
        real x, y
real xcoef(48),ycoef(48)
        real signal(48)

        common /adequ/ xcoef, ycoef

        y = 0.
        x = 0.

        do 54 i = 1,48
          x = x + signal(i) * xcoef(i)
          y = y + signal(i) * ycoef(i)
54    continue

x=2.*x
y=2.*y

```

```

    return
  end

c-----
      subroutine decode(x,y,dibit,xdisp,ydisp,confh,conf1)

c  purpose:  this routine determines the data bits given the x,y coordinates
c            from the equalizer.

c  inputs:   x - the x-coordinate of the demodulated baud.
c            y - the y-coordinate of the demodulated baud.

c  outputs:  dibit - the 2 data bits for the current baud; lsb is first in time.

      integer*4 dibit
      real mag, phaser, x, y, qang, preang, phasech, arctan
      real angle, decang, angdisp, xdisp, ydisp, error
      real angtab
      dimension angtab(4)
      real predecang,diffang
      real confh,conf1
      real desmag

      data angtab / -.75, -.25, .25, .75 /
      data preang / 0. /

      angle = arctan(y,x)
c convert from rectangular to polar coordinates

      decang = angle - phaser
c decang is the angle to be decoded

      call adjust(decang)

c  calculate dibit:

c      preang=qang
c  previously quantized angle

c      qang = angtab(int(2.*decang+2.)+1)
c  quantized angle

c      phasech = qang - preang

```

```

c quantized phase change

c      if(phasech.lt.0.0)phasech=phasech+2.
c      if(phasech.eq.0.0)dibit=2
c phase change of 0
c      if(phasech.eq.0.5)dibit=0
c phase change of 90
c      if(phasech.eq.1.0)dibit=1
c phase change of 180,or -180
c      if(phasech.eq.1.5)dibit=3
c phase change of -90

diffang=decang-predecang
c unquantized phase change

call adjust(diffang)

      predecang=decang
c previous decoded angle update

c compute confidence values :
if(diffang.lt.-.75)then
      dibit=1
      confl=(diffang+1.25)*2.
      confh=-(diffang+.75)*2.
else if(diffang.lt.-.25)then
      dibit=3
      confl=-(diffang+.25)*2.
      confh=(diffang+.75)*2.
else if(diffang.lt.0.25)then
      dibit=2
      confl=(diffang+.25)*2.
      confh=-(diffang-.25)*2
else if(diffang.lt.0.75)then
      dibit=0
      confl=-(diffang-.75)*2.
      confh=(diffang-.25)*2.
else
      dibit=1
      confl=(diffang-.75)*2.
      confh=-(diffang-1.25)*2.
end if

c      calculate x and y values for constellation display:

```

```

mag = sqrt(x*x + y*y)
angdisp = (diffang+.25)
call adjust(angdisp)
angdisp = angdisp * 3.141593

xdisp = mag * cos(angdisp)
ydisp = mag * sin(angdisp)

desmag=.707/2
c scale the confidence by the radius (lower confidence in fade) :
if(mag.lt.desmag)then
  confl=confl*mag/desmag
  confh=confh*mag/desmag
end if

c calculate error angle :

c      error = decang - qang
c      call adjust(error)

c update phase reference for next baud:

phaser = phaser - .5
c                           the .5 comes from .25 (times 180 degrees)
c   of carrier advance per baud plus .25
c   (cr 45 degrees) thus shifting the phase computations
c   from 135,45,-45,-135 to the 90,0,-90,-180 domain
c   call adjust(phaser)

      return
end

c-----
function arctan(y,x)

c 4 quadrant arctangent -1 <= arctan < 1
c -1 corresponds to -180 degrees

      real arctan, y, x

      arctan = 0.0
      if (x .ne. 0.0 .or. y .ne. 0.0) arctan = atan2(y,x)/3.141593

      return

```

```

    end

c-----
    subroutine adjust(value)

c  routine to ensure value is kept in range -1 to 1.

    real value

    value = amod(value,2.)
    if (value .lt. -1.) value = value + 2.
    if (value .ge. 1.)  value = value - 2.

    return
end

c-----
subroutine sim(samples,noise,noisef,mode,iseed,gaus,n,sf,mk)

c-----variables and parameters-----
c noise=signal/noise in dB
c mode = 0 for non-fading, 1 for fading

real samples(3)
    real gaus(256)
c gaussian distribution of noise table
real noise,noisef
real sv(120),nv(120)
real sdb,ndb
integer*4 sinn,nin,n,sf
integer*4 fade,mode,fadecnt
integer*4 iseed
    integer*4 ms10,ms20,ms40,ms100,ms200

c-----variable initialization-----

if (ifirst.eq.0) then
    rgn = (10.**(-noise/20.))
c  compute actual noise scaler from dB

    rgnf = (10.**(-noisef/20.))
c  compute noisef scaler from dB
    ifirst=1

```

```

test=rand(iseed)
  fade = 0
  fadecnt = 0
  ms10 = 0
  ms20 = 0
  ms40 = 0
  ms100 = 0
  ms200 = 0
end if

c-----
do 55 m=1,3

c measure the RMS of past 120 samples of signal
  s = samples(m)
  sinn = mod(sinn+1,120)
  sdb = (sdb**2.)-sv(mod(sinn+1,120)+1)
  sv(sinn+1) = (s**2.)/120.
  sdb = sdb + sv(sinn+1)
  if (sdb.lt.0.) sdb = 0.
  sdb = sqrt(sdb)

c measure the RMS of past 120 samples of noise (direct from table)
  nin = mod(nin+1,120)
  ndb = (ndb**2.)-nv(mod(nin+1,120)+1)
  k = (255.*rand(0)) + 1
  nv(nin+1) = ((gaus(k)/25295.)**2.)/120.
  ndb = ndb + nv(nin+1)
  if (ndb.lt.0.) ndb = 0.
  ndb = sqrt(ndb)

if(mode.eq.1)then
  if(fadecnt.eq.0)then
    if(rand(0).gt..94056)then
      fade=1
      test=rand(0)
      if(test.lt.0.8)then
        fadecnt=120
        ms10 = ms10 + 1
      else if(test.lt.0.9)then
        fadecnt=240
        ms20 = ms20 + 1
      else if(test.lt.0.95)then
        fadecnt=480

```

```

        ms40 = ms40 + 1
else if(test.lt.0.99)then
    fadecnt=1200
        ms100 = ms100 + 1
else
    fadecnt=2400
        ms200 = ms200 + 1
end if
else
    fade=0
    fadecnt=120
end if
else
    fadecnt=fadecnt-1
end if

if((n.eq.sf).and.(mk.eq.1680).and.(m.eq.3))then
    write(6,*)' number of 10ms fades in ',sf,
*' runs = ',ms10
    write(6,*)' number of 20ms fades in ',sf,
*' runs = ',ms20
    write(6,*)' number of 40ms fades in ',sf,
*' runs = ',ms40
    write(6,*)' number of 100ms fades in ',sf,
*' runs = ',ms100
    write(6,*)' number of 200ms fades in ',sf,
*' runs = ',ms200
    end if
end if

if((mode.eq.0).or.((mode.eq.1).and.(fade.eq.0)))then
c not in fade
    if (rand(0).ge.0.5) then
        if (ndb.ne.0.) samples(m) = samples(m) +
1           (gaus(k)/25295.)*(sdb/ndb)*(rgn)
    else
        if (ndb.ne.0.) samples(m) = samples(m) -
1           (gaus(k)/25295.)*(sdb/ndb)*(rgn)
    end if
end if

if((mode.eq.1).and.(fade.eq.1))then
c we are in fade
    if (rand(0).ge.0.5) then
c make positive noise

```

```

        if (ndb.ne.0.) samples(m) = samples(m) +
1               (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
        else
c  make negative noise
        if (ndb.ne.0.) samples(m) = samples(m) -
1               (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
        end if
end if

c scale signal down in fade :
if((mode.eq.1).and.(fade.eq.1))samples(m)=samples(m)/10.

55      continue

return
end

c*****variables and parameters-----
c noise=signal/noise in dB
c mode = 0 for non-fading, 1 for fading

real samples(3)
      real gaus(256)
c**** gaussian distribution of noise table
real noise,noisef,bprob
real sv(120),nv(120)
real sdb,ndb,rtest
integer*4 sinn,nin
integer*4 fade,mode,fadecnt
integer*4 iseed,bwidth

c-----variable initialization-----
if (ifirst.eq.0) then
  rgn = (10.**(-noise/20.))
c**** compute actual noise scaler from dB
  rgnf = (10.**(-noisef/20.))
c**** compute noisef scaler from dB
  ifirst=1
  test=rand(iseed)

```

```

        fade = 0
        fadecnt = 0
        rtest = 1. - (1.-bprob)/120
end if

c-----
do 55 m=1,3

***** measure the RMS of past 120 samples of signal
s = samples(m)
sinn = mod(sinn+1,120)
sdb = (sdb**2.)-sv(mod(sinn+1,120)+1)
sv(sinn+1) = (s**2.)/120.
sdb = sdb + sv(sinn+1)
if (sdb.lt.0.) sdb = 0.
sdb = sqrt(sdb)

***** measure the RMS of past 120 samples of noise (direct from table)
nin = mod(nin+1,120)
ndb = (ndb**2.)-nv(mod(nin+1,120)+1)
k = (255.*rand(0)) + 1
nv(nin+1) = ((gaus(k)/25295.)**2.)/120.
ndb = ndb + nv(nin+1)
if (ndb.lt.0.) ndb = 0.
ndb = sqrt(ndb)

if(mode.eq.1)then
  if(fadecnt.eq.0)then
    if(rand(0).gt.rtest)then
      fade=1
      fadecnt = bwidth
    else
      fade=0
      fadecnt=0
    end if
  else
    fadecnt=fadecnt-1
  end if
end if

***** not in fade
if((mode.eq.0).or.((mode.eq.1).and.(fade.eq.0)))then
  if (rand(0).ge.0.5) then
    if (ndb.ne.0.) samples(m) = samples(m) +

```

```

1           (gaus(k)/25295.)*(sdb/ndb)*(rgn)
else
  if (ndb.ne.0.) samples(m) = samples(m) -
1           (gaus(k)/25295.)*(sdb/ndb)*(rgn)
end if
end if

***** we are in fade
if((mode.eq.1).and.(fade.eq.1))then
***** make positive noise
  if (rand(0).ge.0.5) then
    if (ndb.ne.0.) samples(m) = samples(m) +
1           (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
***** make negative noise
  else
    if (ndb.ne.0.) samples(m) = samples(m) -
1           (gaus(k)/25295.)*(sdb/ndb)*(rgnf)
  end if
end if

***** scale signal down in fade :
if((mode.eq.1).and.(fade.eq.1))samples(m)=samples(m)/200.

55      continue

return
end

*****
c          encodeham
c
c FUNCTION
c          This subroutine calculates the parity bits necessary
c to form the codeword.
c
c
c SYNOPSIS
c          encodeham(codelength1,codelength2,hmatrix,
c          paritybit,codeword)
c
c          formal
c
c          data    I/O
c          name    type    type    function

```

```

c -----
c      codelength1 int i number of data bits (63)
c      codelength2 int i number of information bits (57)
c      hmatrix int i vector to encode an decode by
c      paritybit int o overall parity bit
c      codeword int o encoded stream (paritybits at end)
c
c=====
c
c      c DESCRIPTION
c
c      c This subroutine is part of a set of subroutines which perform
c      c a Generalized Hamming Code.  As you know, Hamming codes are perfect
c      c codes and can only detect and correct one error.  We added an overall
c      c parity checkbit, which allows us to detect 2 errors.  When 2 errors
c      c are detected, (in subroutine decodeham.f) no correction attempt is
c      c made.  This would most likely result in more errors.  Instead, a flag
c      c is sent to the calling program notifying it of multiple errors so
c      c that smoothing may be attempted.  The Hamming codes presently supported
c      c by the routines are (63,57), (31,26), (15,11), and shortened variations
c      c thereof.  It could be made even more general by making minor modifications
c      C to the dectobin.f subroutine.  This routine at present will calculate
c      c a maximum of 6 bits.
c
c      c Hamming routines consist of the following files:
c
c      c matrixgen - generates the hmatrix and syndrometable.
c      c dectobin - does a simple decimal to binary conversion.
c      c encodeham - generates the codeword and overall paritybit.
c      c decodeham - recovers infobits, checks for errors, corrects 1
c      c error, and sends out flag for smoothing.
c
c
c      c
c      c      This subroutine performs the Hamming encode function.
c      c It will calculate the necessary parity bits, depending on which code
c      c is requested, and will add the overall parity bit to the end of the
c      c codeword generated.
c
c
c=====
c
c      c REFERENCES
c
c      c Lin and Costello : Error Control Coding
c      c Berlekamp : Algebraic Coding Theory

```

```

c
c*****subroutine encodeham(codelength1,codelength2,hmatrix,
c      1      paritybit,codeword)
c
integer*4 codelength1,codelength2,paritybit
integer*4 codeword(codelength1),hmatrix(codelength1)
integer*4 parityflag,temp1,temp2,i,temp3
c
paritybit=0
parityflag=0
c *** parityflag = 0 if not using the extra parity bit.
temp1=codelength1-codelength2
temp2=0
temp3=0
c
c First generate the parity bits for the Hamming codeword. This is
c relatively straightforward. hmatrix was generated in matrixgen.f,
c which is called as part of the Hamming initialization routines.
c
do 10 i=1, codelength2
    if(codeword(i).ne.0) temp2= xor(temp2,hmatrix(i))
10 continue
c
c since the hmatrix is stored in a packed decimal format, the parity
c bits must be unpacked and appended to the end of the bitsteam.
c after this routine you will have the complete codeword.
c
call dectobin(temp1,temp2,codeword(codelength2+1))
c
c Now I check to see if the parityflag is set, indicating the user
c requests an overall parity bit be generated. Normally this will
c be the case.
c
temp2=0
if (parityflag.eq.1)then
    do 20 i=1,codelength1
        temp2 = xor(temp2,codeword(i))
        if (codeword(i).ne.0) temp3=temp3+1
20    continue
    paritybit=temp2
end if
c
return

```

```
end
```

```
=====
c
c ROUTINE
c           decodeham
c
c FUNCTION
c           This subroutine decodes the bitstream generated by
c encodeham. It will correct a single error, and detect 2
c errors.
c
c
c SYNOPSIS
c           subroutine decodeham(codelength1,codelength2,hmatrix,
c syndrometable,paritybit,codeword,myerror)
c
c formal
c
c           data    I/O
c      name      type   type   function
c -----
c      codelength1 int i number of data bits
c      codelength2 int i number of information bits
c      hmatrix int i vector to encode an decode by
c      syndrometable int i errormasks used to correct single
c errors
c      paritybit int i overall parity bit
c      codeword int i/o encoded/decoded stream
c      myerror log o flag for 2 error detect
c      synflag int o value 0 or 1, 1 if syndrome .ne. 0
c
c
c=====
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code. As you know, Hamming codes are perfect
c codes and can only detect and correct one error. We added an overall
c parity checkbit, which allows us to detect 2 errors. When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made. This would most likely result in more errors. Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted. The Hamming codes presently supported
```

```

c by the routines are (63,57), (31,26), (15,11), and shortened variations
c thereof. It could be made even more general by making minor modifications
c to the dectobin.f subroutine. This routine at present will calculate
c a maximum of 6 bits.

c

c Hamming routines consist of the following files:

c

c matrixgen - generates the hmatrix and syndrometable.
c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.
c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.

c

c

c This subroutine, decodeham, is responsible for checking for errors,
c correcting the error if there is only one, and sending a smoothing flag
c to the calling routine if there is more than one.

c

c=====
c

c REFERENCES

c

c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
c

c*****
c

        subroutine decodeham(codelength1,codelength2,paritybit,myerror,
1      hmatrix,syndrometable,codeword)

integer*4 codelength1,codelength2,hmatrix(codelength1)
integer*4 syndrometable(codelength1),paritybit
        integer*4 codeword(codelength1),myerror
integer*4 errorflag,parityflag
integer*4 synflag, i, j, temp3

myerror=0
errorflag=0
parityflag=0
c *** parity flag = 0 if not using the extra parity bit
c

c      This part of the routine checks the overall parity of the codeword
c and compares it with the overall paritybit sent. If they are not the
c same that means there is at least one error. If, later on in the routine,
c the syndrome check indicates that there is an error and the parity is

```

```

c correct in this part of the routine, that indicates there are two errors.
c One of the weaknesses of this method is that there is no way of knowing
c if we have 3,5,7,... errors. We always smooth if there are 2,4,6,....
c errors.
c
if (parityflag.eq.1) then
    synflag=0
    do 10 i=1,codeLength1
        synflag= xor(synflag,codeword(i))
10    continue
    if (paritybit.ne.synflag)errorflag=errcrflag+1
end if
c
c This part of the routine generates the syndrome. The syndrome will
c equal zero if there are no errors. synflag accumulates the syndrome
c and is used as the offset in the syndrome table, which tells the
c routine which bit is in error.
c
synflag=0
temp3=0
do 30 i=1,codeLength1
    if(codeword(i).ne.0)synflag = xor(synflag,hmatrix(i))
    if(codeword(i).ne.0)temp3 = temp3 + 1
30 continue
c
c *** Check to see if the parityflag is set and if it is then check
c to see if the parity bit was in error.
c If the parityflag was set and there was an error in the syndrome,
c the errorflag should equal 1.
c If it doesn't, then there are more errors than can be corrected
c and the infobits are passed on unchanged.
c
if (synflag.ne.0)then
    if((errorflag.ne.1) .and. (parityflag.eq.1))then
        myerror = 1
        go to 20
    end if
        j=syndrometable(synflag)
        codeword(j)=xor(codeword(j),1)
end if
c
c *** If the syndrome is equal to zero and the errorflag is set
c (not likely, but must be checked) then more than one error has
c occurred, but it cannot be corrected, so I pass on the infobits
c the same as if there were no errors.

```

```

c
20      continue
return
end
=====
c
c ROUTINE
c dectobin
c
c FUNCTION
c This subroutine converts decimal numbers into a
c binary output vector.
c
c SYNOPSIS
c dectobin(vectorsize, decinteger, binaryvector)
c
c formal
c
c           data   I/O
c      name      type   type   function
c -----
c vectorsize int i output vector length
c decinteger int i decimal number (< 2^32-1)
c binaryvector int o vector containing binary number
c
=====
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code. As you know, Hamming codes are perfect
c codes and can only detect and correct one error. We added an overall
c parity checkbit, which allows us to detect 2 errors. When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made. This would most likely result in more errors. Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted. The Hamming codes presently supported
c by the routines are (63,57), (31,21), (15,11), and shortened variations
c thereof. It could be made even more general by making minor modifications
c to the dectobin.f subroutine. This routine at present will calculate
c a maximum of 6 bits.
c
c Hamming routines consist of the following files:
c
c matrixgen - generates the hmatrix and sydrometable.

```

```

c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.
c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.
c
c
c This routine is used by encodeham to convert the packed decinteger
c into the Hamming paritybits.
c
c*****
c
c REFERENCES
c
c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
c
c*****
c
c subroutine dectobin(vectorsize, decinteger, binaryvector)
c
integer*4 vectorsize, decinteger, binaryvector(vectorsize)
integer*4 i, temp1, twostable(6)
c
data twostable/1,2,4,8,16,32/
c
c Check to see if the decimal integer is larger than the routine can
c convert. This can be easily extended by adding to the twostable.
c
if (decinteger .gt. 63)
  &      print *, 'dectobin: decinteger too large', decinteger
temp1=vectorsize
do 10 i=1,vectorsize
  if(decinteger.ge.twostable(temp1))then
    binaryvector(temp1)=1
    decinteger=decinteger-twostable(temp1)
  else
    binaryvector(temp1)=0
  end if
  temp1=temp1-1
10 continue
return
end
c=====
c
c ROUTINE

```

```

c matrixgen
c
c FUNCTION
c
c This routine is used to generate the H matrix and
c syndrome table necessary for Hamming encode and decode. This
c routine should be called once before calling encodeham and
c decodeham.
c
c SYNOPSIS
c subroutine matrixgen(codelength1,codelength2,
c hmatrix,syndrometable)
c
c formal
c
c           data   I/O
c   name      type   type   function
c   -----
c   codelength1 int i number of data bits (63)
c   codelength2 int i number of information bits (57)
c   hmatrix int o vector to encode an decode by
c   syndrometable int o table containing error masks
c
c=====
c
c DESCRIPTION
c
c This subroutine is part of a set of subroutines which perform
c a Generalized Hamming Code. As you know, Hamming codes are perfect
c codes and can only detect and correct one error. We added an overall
c parity checkbit, which allows us to detect 2 errors. When 2 errors
c are detected, (in subroutine decodeham.f) no correction attempt is
c made. This would most likely result in more errors. Instead, a flag
c is sent to the calling program notifying it of multiple errors so
c that smoothing may be attempted. The Hamming codes presently supported
c by the routines are (63,57), (31,26), (15,11), and shortened variations
c thereof. It could be made even more general by making minor modifications
c to the dectobin.f subroutine. This routine at present will calculate
c a maximum of 6 bits.
c
c Hamming routines consist of the following files:
c
c matrixgen - generates the hmatrix and syndrometable.
c dectobin - does a simple decimal to binary conversion.
c encodeham - generates the codeword and overall paritybit.

```

```

c decodeham - recovers infobits, checks for errors, corrects 1
c error, and sends out flag for smoothing.
c
c This routine is initializes all of the tables necessary to perform
c the Hamming code (G Matrix, Syndrome Table) .
c
c=====
c
c REFERENCES
c
c Lin and Costello : Error Control Coding
c Berlekamp : Algebraic Coding Theory
c
c*****
c
subroutine matrixgen(codelength1,codelength2,hmatrix,syndrometable)
c
integer*4 codelength1,codelength2
    integer*4 hmatrix(codelength1),syndrometable(codelength1)
integer*4 itemplate(6),ptemplate(57),i,temp1
c
c This is the data necessary to construct the G Matrix and the Syndrome
c Table. If a larger code is desired, this table can be easily added to.
c All other routines, except the syndrome table construction,
c are general enough to calculate any size Hamming Code.
c
data itemplate/1,2,4,8,16,32/
data ptemplate/3,5,6,7,9,10,11,12,13,14,15,17,18,19,
    + 20,21,22,23,24,25,26,27,28,29,30,31,33,34,35,36,37,38,39,40,41,
    + 42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,
    + 63/
c
c Construct the parity portion of the hmatrix
c
do 30 i=1,codelength2
    hmatrix(i)=ptemplate(i)
30 continue
c
c Construct the identity portion of the hmatrix.
c
do 20 i=1,(codelength1-codelength2)
    hmatrix((codelength2+i))=itemplate(i)
20 continue
c
c Construct the syndrometable. This routine is rather simple because

```

```

c I chose to arrange my G matrix sequentially (Berlekamp method).
c I placed the parity bits in front in ascending order then added the
c bits left over in ascending order. Since our code is linear I can get
c away with this. If a larger Hamming code is needed, then a new
c exception must be generated for each parity bit.
c
temp1=1
do 10 i=1,codelength1
  if(i.eq.1)then
    syndrometable(i)=codelength2+1
    goto 10
  end if
  if(i.eq.2)then
    syndrometable(i)=codelength2+2
    goto 10
  end if
  if(i.eq.4)then
    syndrometable(i)=codelength2+3
    goto 10
  end if
  if(i.eq.8)then
    syndrometable(i)=codelength2+4
    goto 10
  end if
  if(i.eq.16)then
    syndrometable(i)=codelength2+5
    goto 10
  end if
  if(i.eq.32)then
    syndrometable(i)=codelength2+6
    goto 10
  end if
  syndrometable(i)=temp1
  temp1=temp1+1
c
10 continue
c
return
end

```

C. DATA INPUT

***** Gaussian Input *****

20.	60.	100.	140.	181.	221.	261.	301.
341.	381.	421.	462.	502.	542.	582.	622.
662.	702.	743.	783.	824.	864.	904.	944.
985.	1025.	1065.	1106.	1146.	1187.	1227.	1268.
1309.	1350.	1390.	1431.	1472.	1513.	1553.	1594.
1635.	1676.	1717.	1758.	1798.	1840.	1881.	1922.
1963.	2005.	2046.	2088.	2129.	2170.	2212.	2254.
2296.	2337.	2379.	2421.	2463.	2505.	2546.	2589.
2631.	2673.	2716.	2758.	2800.	2843.	2886.	2928.
2972.	3014.	3057.	3100.	3144.	3186.	3230.	3273.
3316.	3360.	3404.	3448.	3492.	3535.	3579.	3624.
3668.	3712.	3757.	3801.	3846.	3891.	3936.	3981.
4026.	4072.	4117.	4163.	4209.	4254.	4300.	4346.
4392.	4439.	4485.	4532.	4579.	4626.	4673.	4720.
4767.	4815.	4863.	4911.	4959.	5007.	5056.	5104.
5153.	5201.	5251.	5301.	5350.	5400.	5450.	5500.
5550.	5600.	5651.	5702.	5754.	5805.	5857.	5908.
5961.	6013.	6066.	6118.	6171.	6225.	6279.	6333.
6387.	6442.	6496.	6551.	6606.	6662.	6719.	6774.
6831.	6888.	6945.	7003.	7061.	7119.	7178.	7237.
7296.	7356.	7417.	7477.	7538.	7599.	7661.	7724.
7787.	7850.	7914.	7978.	8042.	8108.	8173.	8240.
8306.	8373.	8441.	8510.	8579.	8649.	8719.	8790.
8862.	8935.	9007.	9081.	9156.	9231.	9306.	9383.
9461.	9540.	9619.	9700.	9781.	9863.	9947.	10031.
10117.	10203.	10290.	10380.	10470.	10561.	10654.	10748.
10843.	10941.	11039.	11140.	11241.	11345.	11451.	11558.
11668.	11780.	11893.	12010.	12129.	12250.	12374.	12500.
12631.	12764.	12901.	13041.	13186.	13334.	13488.	13646.
13809.	13978.	14153.	14335.	14524.	14721.	14928.	15143.
15371.	15610.	15864.	16134.	16423.	16734.	17071.	17439.
17847.	18305.	18827.	19440.	20186.	21150.	22545.	25295.

***** Golay Decoder Input *****

11	10	362	9	361	329	11593	8	360	328
11592	296	11560	10536	22946	7	359	327	11591	295
11559	10535	16869	263	11527	10503	18563	9479	24198	21889
20014	6	358	326	11590	294	11558	10534	20033	262
11526	10502	17932	9478	24199	15812	21667	230	11494	10470
21965	9446	24200	17506	22916	8422	24201	23141	15425	24203
756	18957	24202	5	357	325	11589	293	11557	10533
16871	261	11525	10501	20929	9477	19844	24145	21699	229
11493	10469	16873	9445	16874	16875	527	8421	22050	23142
23980	14755	23105	20610	16872	197	11461	10437	23682	9413
23086	20908	21763	8389	18925	23143	21795	16449	21827	21859
675	7365	12385	23144	21073	22084	19874	24001	16870	23146
16836	723	23147	17900	24197	23145	21731	4	356	324
11588	292	11556	10532	22161	260	11524	10500	18659	9476
19845	15814	24065	228	11492	10468	18691	9444	14401	24173
22918	8420	18755	18787	579	23088	21997	20642	18723	196
11460	10436	23714	9412	16803	15816	22919	8388	23201	15817
21101	15818	18978	494	15819	7364	20015	20993	22921	22085
22922	22923	716	13698	16837	24241	18627	19553	24196	15815
22920	164	11428	10404	23746	9380	19848	22625	18893	8356
19849	22029	23087	19851	620	20706	19850	7332	23181	17868
22113	22086	24099	20738	16868	24033	16838	20770	18595	20802
19847	642	20834	6308	23874	23906	738	22087	20961	20016
23842	21027	16839	18817	23810	24269	19846	15813	21635	22089
16840	15779	23778	690	22091	22090	22917	16843	526	23140
16842	22088	16841	20674	17825	3	355	323	11587	291
11555	10531	24012	259	11523	10499	18660	9475	17889	21104
21701	227	11491	10467	18692	9443	23219	17602	20897	8419
18756	18788	580	14757	16770	24271	18724	195	11459	10435
23183	9411	16804	17634	21765	8387	19906	23969	21797	23116
21829	21861	677	7363	12449	17698	24176	17730	18926	546
17762	22031	23085	20940	18628	19585	24195	17666	21733	163
11427	10403	20013	9379	21058	22657	21766	8355	24272	15746
21798	14759	21830	21862	678	7331	12481	24244	22978	14760
24100	20044	16867	14761	21103	17921	18596	461	14763	14762
21734	6307	12513	18958	21800	24175	21832	21864	680	21028
21833	21865	681	21866	682	683	21	12641	385	15780
12609	23184	12577	17570	21767	24130	12545	23139	21799	14758
21831	21863	679	131	11395	10371	18695	9347	16806	22689
19938	8323	18759	18791	583	24226	23182	17836	18727	7299
18760	18792	584	20972	24101	22030	18728	18794	586	587

18	19649	18761	18793	585	6275	16809	22124	17857	16811
525	24210	16810	21029	24044	23042	18662	19681	16808	15811
21668	24270	22146	15781	18694	19713	16807	17538	22915	19745
18758	18790	582	609	19809	19777	18726	5251	21998	22817
21004	22849	24103	705	22881	21030	13377	24174	18661	18959
19843	22785	21700	19970	24105	15782	18693	24107	753	22753
24106	23212	18757	18789	581	14756	24104	20578	18725	21032
23154	15783	23650	14722	16805	22721	21764	657	21035	21034
21796	21033	21828	21860	676	15786	12417	493	15787	22083
24102	15785	21102	21031	16835	15784	18629	19617	23010	24076
21732	2	354	322	11586	290	11554	10530	22952	258
11522	10498	22953	9474	22954	22955	717	226	11490	10466
21100	9442	14465	17603	24242	8418	22053	24078	15553	20047
16771	20644	22951	194	11458	10434	23716	9410	21996	17635
21006	8386	19907	22162	15585	16545	18980	24172	22950	7362
23120	17699	15617	17731	19877	547	17763	13700	15681	15713
481	23214	24194	17667	15649	162	11426	10402	23748	9378
21059	22126	17793	8354	22055	15747	20048	16577	24046	20708
22949	7330	22056	18849	22979	24268	19878	20740	16866	22059
689	20772	22058	20804	22057	644	20836	6306	23876	23908
740	16641	19879	23119	23844	16673	23180	17869	23812	513
16737	16705	21602	20974	19881	22028	23780	19883	621	17571
19882	24131	22054	23138	15521	16609	19880	20676	18892	130
11394	10370	23749	9346	14561	18956	19939	8322	21007	20001
21964	24227	18982	20709	22948	7298	14625	23215	17933	14689
449	20741	14657	13702	24275	20773	18530	20805	14593	645
20837	6274	23877	23909	741	23187	18984	21921	23845	13703
18985	23043	23813	18987	593	15810	18986	13704	22147	20046
23781	24079	14529	17539	22914	428	13707	13706	15489	13705
18983	20677	22128	5250	23878	23910	742	17901	23216	20743
23846	23118	13409	20775	23814	20807	19842	647	20839	19971
18924	20776	23782	20808	14497	648	20840	20809	22052	649
20841	650	20842	20	651	23914	746	747	23	14723
23881	23913	745	22127	23880	23912	744	16513	18981	20710
23848	23073	23879	23911	743	22082	19876	20742	23847	13701
16834	20774	23815	20806	23011	646	20838	98	11362	10338
22017	9314	21061	17638	19940	8290	19910	15749	24209	24228
16775	18881	22947	7266	24045	17702	22981	17734	16776	550
17766	23169	16777	22125	18562	16779	524	17670	16778	6242
19912	17703	18860	17735	24257	551	17767	19915	622	23044
19914	20973	19913	17671	21666	17737	22148	553	17769	554
17770	17	555	24133	19911	17704	15457	17736	16774	552
17768	5218	21065	15752	22983	21067	658	24077	21066	15754
13441	492	15755	23153	21064	15753	21698	19972	22986	22987
718	21985	21063	17605	22985	24134	22051	15751	22984	14754

16773	20611	24161	23213	17935	21089	23683	14724	21062	17637
21762	24135	19909	15750	21794	16481	21826	21858	674	24136
12353	17701	22982	17733	19875	549	17765	754	24139	24138
21005	24137	23012	17669	21730	4194	23084	20941	19945	24232
19946	19947	623	24233	13473	23046	18658	757	24235	24234
19944	19973	22150	23937	18690	23117	14433	17604	19943	17902
18754	18786	578	24231	16772	20643	18722	18913	22151	23048
23715	14725	16802	17636	19942	23050	19908	720	23051	24230
18979	23049	20865	22155	692	17700	22154	17732	22153	548
17764	13699	22152	23047	18626	19521	23013	17668	24013	19975
13569	22097	23747	14726	21060	22593	19941	13665	417	15748
13633	24229	13601	20707	17934	624	19979	19978	22980	19977
24098	20739	21932	19976	13537	20771	18594	20803	23014	643
20835	14729	23875	23907	739	460	14731	14730	23843	21026
13505	23045	23811	14728	23015	20045	21634	19974	22149	15778
23779	14727	23016	17572	18945	24132	23017	21953	20012	23019
719	20675	23018	1	353	321	11585	289	11553	10529
20038	257	11521	10497	20933	9473	17891	21895	24068	225
11489	10465	24273	9441	14466	21896	20899	8417	19981	21897
15554	21898	23109	684	21899	193	11457	10433	20041	9409
20042	20043	626	8385	23204	23971	15586	16546	14764	23185
20040	7361	12451	20996	15618	23021	22064	24005	20039	18990
15682	15714	482	19587	24193	21894	15650	161	11425	10401
20936	9377	24237	22659	17794	8353	20938	20939	654	16578
23111	19949	20937	7329	12483	18850	22116	21105	23112	24006
16865	24036	23113	17923	20935	23115	722	21893	23114	6305
12515	22063	23053	16642	20964	24007	20037	16674	24177	18820
20934	514	16738	16706	21601	12643	387	24009	12611	24010
12579	750	24011	22157	12547	23137	15522	16610	23110	24008
17828	129	11393	10369	15788	9345	14562	22691	24072	8321
23206	20002	24073	21069	24074	24075	752	7297	14626	20998
22117	14690	450	18991	14658	24037	21036	22989	18529	19651
14594	21892	24071	6273	23208	20999	17859	24108	20965	21922
20036	23211	725	18821	23210	19683	23209	15809	24070	21002
24141	656	21003	19715	14530	21001	22913	19747	23207	21000
15490	611	19811	19779	17829	5249	18992	22819	22119	22851
20966	707	22883	24039	13410	18822	20932	22062	19841	22787
24069	24040	22122	22123	691	16812	14498	22755	22121	751
24043	24042	22120	24041	23108	20545	17830	19917	20969	18824
23617	20971	655	22723	20970	18826	23205	588	18827	16514
20968	18825	17831	23074	12419	20997	22118	22081	20967	24004
17832	24038	16833	18823	17833	19619	17834	17835	557	97
11361	10337	22018	9313	17896	22692	20903	8289	17897	23974
23148	17899	559	18882	17898	7265	12485	19950	20905	24144
20906	20907	653	23170	24238	17925	18561	19652	17895	21891

20904	6241	12517	23976	17860	22158	24258	16876	20035	23978
21072	749	23979	19684	17894	23977	21665	12645	389	23218
12613	19716	12581	17473	20902	19748	12549	23975	15458	612
19812	19780	23054	5217	12518	22820	24143	22852	19982	708
22884	22130	13442	17927	20931	24204	17893	22788	21697	12646
	390	17928	12614	21986	12582	22756	20901	17930	12550
17931	14753	23107	17929	24162	12647	391	21090	12615	18989
12583	22724	21761	23022	12551	23973	21793	16482	21825	21857
	673	395	12	12650	394	12649	393	24003	12617
392	17926	12616	19620	12584	21071	21729	4193	24211	22821
17862	22853	22092	709	22885	16844	13474	22159	18657	19686
17892	22789	24067	22061	23055	23938	18689	19718	14434	22757
20900	19750	18753	18785	577	614	19814	19782	18721	18914
17866	17867	558	19719	16801	22725	17865	19751	23203	23972
17864	615	19815	19783	20866	19752	12452	20995	17863	616
19816	19784	24239	617	19817	19785	18625	19	619	618
19818	22857	13570	713	22889	714	22890	22	715	13666
	418	22824	13634	22856	13602	712	22888	21070	12484
22115	22855	24097	711	22887	24035	13538	17924	18593	19653
22160	22791	15820	24240	12516	22822	17861	22854	20963	710
22886	21025	13506	18819	19983	19685	24142	22790	21633	12644
	388	15777	12612	19717	12580	22758	18946	19749	12548
24276	613	19813	19781	17827	65	11329	10305	22019	9281
14564	24207	17797	8257	24140	20004	15590	16581	22163	18883
22945	7233	14628	18853	15622	14692	452	23152	14660	23171
15686	15718	486	24109	14596	21890	15654	6209	21037	22988
15623	16645	24259	21924	20034	16677	15687	15719	487	517
16741	16709	15655	24243	15688	15720	488	21068	14532	17505
15656	15722	490	491	15	16613	15689	15721	489	5185
23151	18855	17801	16646	17802	17803	556	16678	13443	24277
20930	518	16742	16710	17800	18858	24208	589	18859	21987
14500	18857	17799	19916	22049	18856	15557	16614	23106	20609
24163	16680	22094	21091	23681	520	16744	16712	17798	521
16745	16713	15589	16	523	522	16746	23076	12386	18854
15621	16647	19873	24002	23220	16679	15685	15717	485	519
16743	16711	15653	4161	14631	20008	23186	14695	455	21926
14663	20010	13475	625	20011	23020	14599	20009	24066	14697
	457	23939	14665	459	14	14698	458	22096	14632
15556	14696	456	20641	14664	18915	19980	21929	23713	21930
14566	685	21931	24206	23202	20006	15588	16548	18977	21928
20867	23077	14630	20994	15620	14694	454	21927	14662	13697
15684	15716	484	19554	14598	24274	15652	22156	13571	16878
23745	24178	14565	22626	17796	13667	419	20005	13635	16580
13603	20705	22095	23078	14629	18852	22114	14693	453	20737
14661	24034	13539	20769	23052	20801	14597	641	20833	23079

23873 23905 737 16644 20962 21925 23841 16676 13507 18818
23809 516 16740 16708 23150 721 23083 23082 23777 23081
14533 19948 18947 23080 21106 21955 15524 16612 24236 20673
17826 3137 22026 22027 688 19884 24262 18888 22025 23175
13476 18889 22024 18890 17890 590 18891 23176 20049 23940
22023 21989 14467 17601 20898 724 23179 23178 15555 23177
16769 18887 24165 18916 24265 21093 22022 24267 758 17633
24266 22060 19905 23970 15587 16547 24264 18886 20868 16845
12450 17697 15619 17729 24263 545 17761 23174 15683 15715
483 19586 22093 17665 15651 24110 13572 21094 22021 21991
21057 22658 17795 13668 420 15745 13636 16579 13604 18885
24167 21993 12482 18851 22977 687 21995 21994 24168 23173
13540 17922 24169 21992 24170 24171 755 21098 12514 659
21099 16643 24261 21097 15821 16675 13508 21096 23121 515
16739 16707 21569 12642 386 21095 12610 21990 12578 17569
18948 24129 12546 21956 15523 16611 21038 22956 24166 18918
13573 23943 22020 21040 14563 22690 19937 13669 421 20003
13637 24225 13605 18884 20870 23946 14627 748 23947 14691
451 23945 14659 23172 13541 23944 18497 19650 14595 16877
23217 591 18923 18922 17858 18921 24260 21923 20872 18920
13509 23041 20873 19682 20874 20875 652 18919 22145 23942
23149 19714 14531 17537 18949 19746 24112 21957 15491 610
19810 19778 20871 13672 424 22818 13640 22850 13608 706
22882 427 13 13674 426 13673 425 22786 13641 19969
13575 23941 21039 21988 14499 22754 18950 13671 423 21958
13639 18988 13607 20577 24164 18917 13574 21092 23649 14721
22129 22722 18951 13670 422 21959 13638 16515 13606 24111
20869 23075 12418 21960 18953 24205 18954 18955 592 21962
13542 686 21963 19618 23009 21961 18952

APPENDIX B: Simulation Data

A. INMARSAT Channel

***** QRC *****

```
# errors corrected = 2
there were no errors in QRC cw
# errors corrected = 2
success = 763
you just completed superframe # 999
# errors corrected = 2
# errors corrected = 4
fail = 236
total errors in sf = 8
number of 10ms fades in 1000 runs = 1842
number of 20ms fades in 1000 runs = 254
number of 40ms fades in 1000 runs = 103
number of 100ms fades in 1000 runs = 87
number of 200ms fades in 1000 runs = 24
you just completed superframe # 1000
iallerr= 3955 itotbitct= 143856 n = 1000
the total number of failures = 236
the total number of successes = 763
This was a nogolay run
This was a QRC BE count run
This run used fading (1=yes,0=no) 1
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

***** Soft Decision Golay *****

```
success = 746
you just completed superframe # 999
success = 747
number of 10ms fades in 1000 runs = 1909
number of 20ms fades in 1000 runs = 239
number of 40ms fades in 1000 runs = 129
number of 100ms fades in 1000 runs = 86
number of 200ms fades in 1000 runs = 32
you just completed superframe # 1000
the total number of failures = 252
```

the total number of successes = 747
This was a soft golay run
This run used fading (1=yes,0=no) 1
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000

B. Gaussian Channel

***** No Code *****

```
errors in 100 bits = 18
errors in 3000 bits = 337
errors in 3000 bits = 352
errors in 3000 bits = 364
errors in 3000 bits = 367
you just completed superframe # 200
the total number of failures = 198
the total number of successes = 0
This was a nogolay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 3.00000
```

```
errors in 100 bits = 11
errors in 3000 bits = 249
errors in 3000 bits = 268
errors in 3000 bits = 265
errors in 3000 bits = 262
you just completed superframe # 200
the total number of failures = 196
the total number of successes = 1
This was a nogolay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 4.00000
```

```
errors in 100 bits = 7
errors in 3000 bits = 179
errors in 3000 bits = 182
errors in 3000 bits = 175
errors in 3000 bits = 176
you just completed superframe # 200
the total number of failures = 197
the total number of successes = 2
This was a nogolay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 5.00000
```

```
errors in 100 bits = 4
errors in 3000 bits = 125
errors in 3000 bits = 128
errors in 3000 bits = 103
errors in 3000 bits = 116
you just completed superframe # 200
the total number of failures = 192
the total number of successes = 7
This was a nogolay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 6.00000
```

***** Hard Decision Golay *****

```
errors in 100 bits = 14
errors in 3000 bits = 240
errors in 3000 bits = 277
errors in 3000 bits = 268
errors in 3000 bits = 278
you just completed superframe # 200
the total number of failures = 171
the total number of successes = 26
This was a hard golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 3.00000
```

```
errors in 100 bits = 1
errors in 3000 bits = 111
errors in 3000 bits = 146
errors in 3000 bits = 145
errors in 3000 bits = 136
you just completed superframe # 200
the total number of failures = 123
the total number of successes = 72
This was a hard golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 4.00000
```

```
errors in 100 bits = 0
errors in 3000 bits = 41
errors in 3000 bits = 52
errors in 3000 bits = 48
errors in 3000 bits = 36
you just completed superframe # 200
the total number of failures = 57
the total number of successes = 140
This was a hard golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 5.00000
```

```
errors in 100 bits = 0
errors in 3000 bits = 5
errors in 3000 bits = 0
errors in 3000 bits = 4
errors in 3000 bits = 7
you just completed superframe # 200
the total number of failures = 13
the total number of successes = 186
This was a hard golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 6.00000
```

***** Soft Decision Golay *****

```
errors in 100 bits = 10
errors in 3000 bits = 146
errors in 3000 bits = 192
errors in 3000 bits = 172
errors in 3000 bits = 182
you just completed superframe # 200
the total number of failures = 135
the total number of successes = 62
This was a soft golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 3.00000
```

```
errors in 100 bits = 0
errors in 3000 bits = 62
errors in 3000 bits = 75
errors in 3000 bits = 88
errors in 3000 bits = 68
you just completed superframe # 200
the total number of failures = 77
the total number of successes = 122
This was a soft golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 4.00000
```

```
errors in 100 bits = 0
errors in 3000 bits = 18
errors in 3000 bits = 13
errors in 3000 bits = 24
errors in 3000 bits = 10
you just completed superframe # 200
the total number of failures = 24
the total number of successes = 175
This was a soft golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 5.00000
```

```
errors in 100 bits = 0
errors in 3000 bits = 7
you just completed superframe # 200
the total number of failures = 5
the total number of successes = 194
This was a soft golay run
This run used fading (1=yes,0=no) 0
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 6.00000
```

C. Constant Burst Width Channel

KEY:

fade widths (120, 240, 480, 1200, 2400) correspond to
burst widths (10, 20, 40, 100, 200) milliseconds.

***** No Code *****

```
errors in 100 bits = 4
errors in 3000 bits = 101
errors in 3000 bits = 95
errors in 3000 bits = 86
errors in 3000 bits = 70
you just completed superframe # 200
the total number of failures = 106
the total number of successes = 93
This was a nogolay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 120
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 7
errors in 3000 bits = 178
errors in 3000 bits = 190
errors in 3000 bits = 188
errors in 3000 bits = 102
you just completed superframe # 200
the total number of failures = 114
the total number of successes = 85
This was a nogolay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 240
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 0
errors in 3000 bits = 283
errors in 3000 bits = 265
errors in 3000 bits = 324
errors in 3000 bits = 218
you just completed superframe # 200
```

```
the total number of failures = 123
the total number of successes = 74
This was a nogolay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 480
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 29
errors in 3000 bits = 472
errors in 3000 bits = 606
errors in 3000 bits = 482
errors in 3000 bits = 462
you just completed superframe # 200
the total number of failures = 135
the total number of successes = 62
This was a nogolay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 1200
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 26
errors in 3000 bits = 798
errors in 3000 bits = 816
errors in 3000 bits = 852
errors in 3000 bits = 883
you just completed superframe # 200
the total number of failures = 156
the total number of successes = 39
This was a nogolay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 2400
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

***** Hard Decision Golay *****

```
errors in 100 bits = 0
errors in 3000 bits = 10
errors in 3000 bits = 13
errors in 3000 bits = 7
errors in 3000 bits = 13
you just completed superframe # 200
the total number of failures = 11
the total number of successes = 188
This was a hard golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 120
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 0
errors in 3000 bits = 25
errors in 3000 bits = 40
errors in 3000 bits = 58
errors in 3000 bits = 18
you just completed superframe # 200
the total number of failures = 41
the total number of successes = 158
This was a hard golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 240
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 0
errors in 3000 bits = 270
errors in 3000 bits = 257
errors in 3000 bits = 234
errors in 3000 bits = 305
you just completed superframe # 200
the total number of failures = 102
the total number of successes = 97
This was a hard golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 480
s/n during fade (dB) = -24.0000
```

s/n during non-fade (dB) = 99.0000

errors in 100 bits = 0
errors in 3000 bits = 698
errors in 3000 bits = 543
errors in 3000 bits = 733
errors in 3000 bits = 616
you just completed superframe # 200
the total number of failures = 151
the total number of successes = 48
This was a hard golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 1200
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000

errors in 100 bits = 14
errors in 3000 bits = 739
errors in 3000 bits = 972
errors in 3000 bits = 986
you just completed superframe # 200
the total number of failures = 133
the total number of successes = 19
This was a hard golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 2400
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000

***** Soft Decision Golay *****

```
errors in 100 bits = 0
errors in 3000 bits = 0
you just completed superframe # 200
the total number of failures = 2
the total number of successes = 197
This was a soft golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 120
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 0
errors in 3000 bits = 0
errors in 3000 bits = 76
errors in 3000 bits = 10
errors in 3000 bits = 26
you just completed superframe # 200
the total number of failures = 21
the total number of successes = 178
This was a soft golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 240
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000
```

```
errors in 100 bits = 0
errors in 3000 bits = 111
errors in 3000 bits = 137
errors in 3000 bits = 133
errors in 3000 bits = 153
you just completed superframe # 200
the total number of failures = 60
the total number of successes = 139
This was a soft golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 480
s/n during fade (dB) = -24.0000
```

s/n during non-fade (dB) = 99.0000

errors in 100 bits = 0
errors in 3000 bits = 412
errors in 3000 bits = 521
errors in 3000 bits = 647
errors in 3000 bits = 509
you just completed superframe # 200
the total number of failures = 133
the total number of successes = 66
This was a soft golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 1200
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000

errors in 100 bits = 8
errors in 3000 bits = 769
errors in 3000 bits = 711
errors in 3000 bits = 976
errors in 3000 bits = 757
you just completed superframe # 200
the total number of failures = 160
the total number of successes = 39
This was a soft golay run
This run used fading (1=yes,0=no) 1
fading width, bwidth = 2400
s/n during fade (dB) = -24.0000
s/n during non-fade (dB) = 99.0000

Hamming Codeword Interleaving Table

CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8	CW9
721	731	751	761	781	791	811	821	841
991	1001	1021	1031	1051	1061	1081	1091	1111
1261	1271	1291	1301	1321	1331	1351	1361	1381
1531	1541	1561	1571	1591	1601	1621	1631	1651
1801	1811	1831	1841	1861	1871	1891	1901	1921
2071	2081	2101	2111	2131	2141	2161	2171	2191
2341	2351	2371	2381	2401	2411	2431	2441	2461
2611	2621	2641	2651	2671	2681	2701	2711	2731

CW10	CW11	CW12	CW13	CW14	CW15	CW16	CW17	CW18
851	871	881	901	911	931	941	961	971
1121	1141	1151	1171	1181	1201	1211	1231	1241
1391	1411	1421	1441	1451	1471	1481	1501	1511
1661	1681	1691	1711	1721	1741	1751	1771	1781
1931	1951	1961	1981	1991	2011	2021	2041	2051
2201	2221	2231	2251	2261	2281	2291	2311	2321
2471	2491	2501	2521	2531	2551	2561	2581	2591
2741	2761	2771	2791	2801	2821	2831	2851	2861

Golay Codeword Interleaving Table

CW1	CW2	CW3	CW4	CW5	CW6
721	751	781	811	841	871
731	761	791	821	851	881
901	931	961	991	1021	1051
911	941	971	1001	1031	1061
1081	1111	1141	1171	1201	1231
1091	1121	1151	1181	1211	1241
1261	1291	1321	1351	1381	1411
1271	1301	1331	1361	1391	1421
1441	1471	1501	1531	1561	1591
1451	1481	1511	1541	1571	1601
1621	1651	1681	1711	1741	1771
1631	1661	1691	1721	1751	1781
1801	1831	1861	1891	1921	1951
1811	1841	1871	1901	1931	1961
1981	2011	2041	2071	2101	2131
1991	2021	2051	2081	2111	2141
2161	2191	2221	2251	2281	2311
2171	2201	2231	2261	2291	2321
2341	2371	2401	2431	2461	2491
2351	2381	2411	2441	2471	2501
2521	2551	2581	2611	2641	2671
2531	2561	2591	2621	2651	2681
2701	2731	2761	2791	2821	2851
2711	2741	2771	2801	2831	2861

QRC Codeword Interleaving Table

CW1	CW2	CW3
721	781	841
731	791	851
751	811	871
761	821	881
1081	1141	1201
1091	1151	1211
1111	1171	1231
1121	1181	1241
1441	1501	1561
1451	1511	1571
1471	1531	1591
1481	1541	1601
1801	1861	1921
1811	1871	1931
1831	1891	1951
1841	1901	1961
2161	2221	2281
2171	2231	2291
2191	2211	2311
2201	2261	2321
2521	2581	2641
2531	2591	2651
2551	2611	2671
2561	2621	2681

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